Urban Aerosol-Induced Changes of Precipitation

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and

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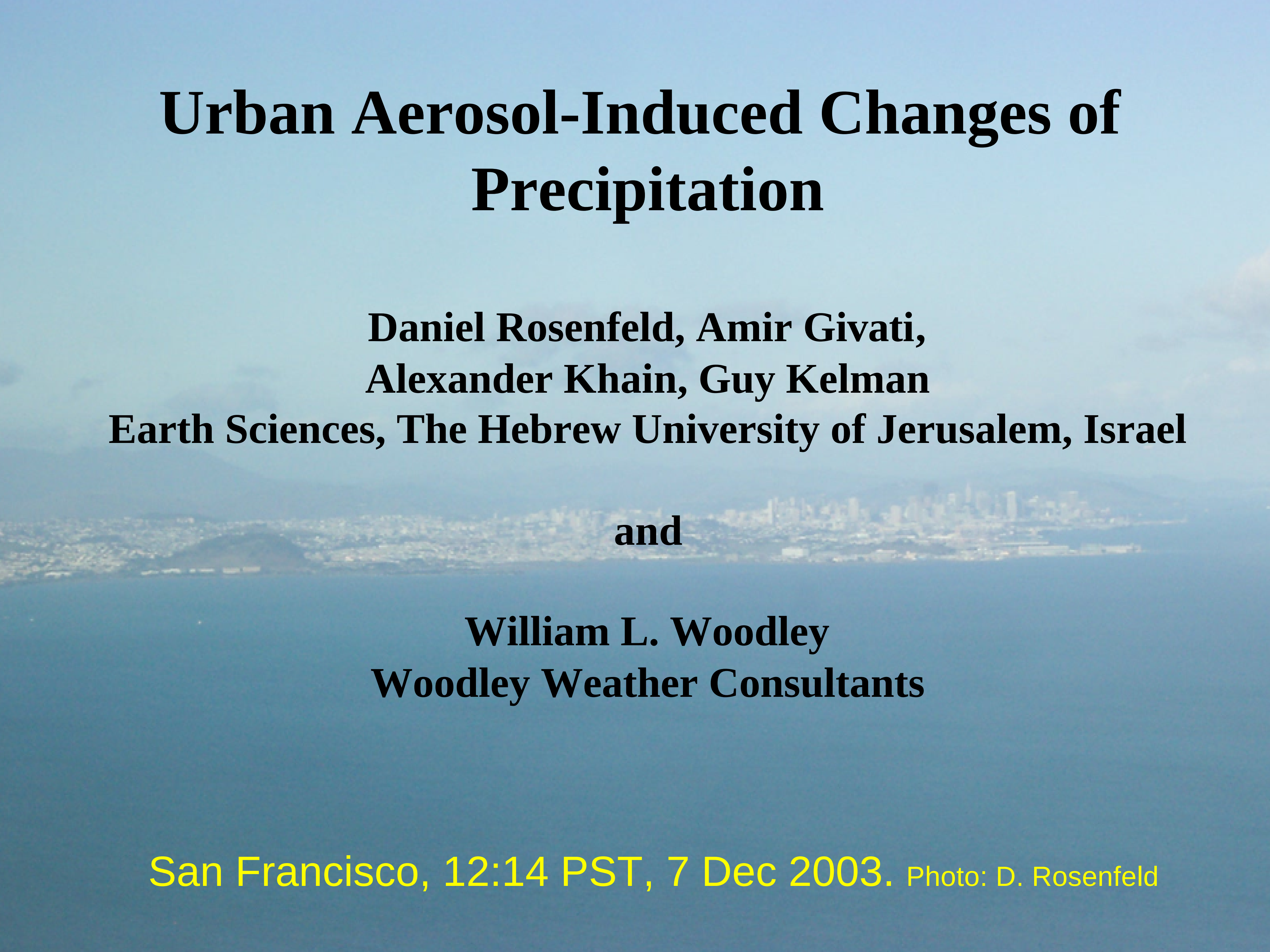
Woodley Weather Consultants



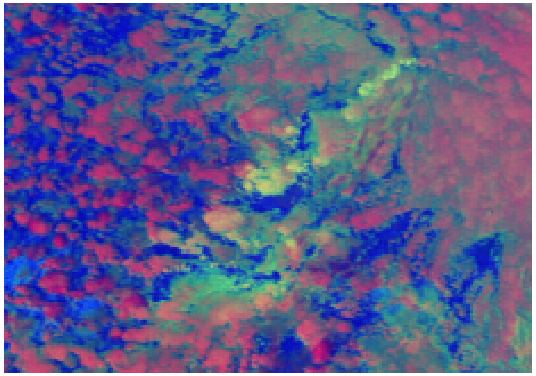
San Francisco, 12:14 PST, 7 Dec 2003. Photo: D. Rosenfeld


Dr. Daniel Rosenfeld

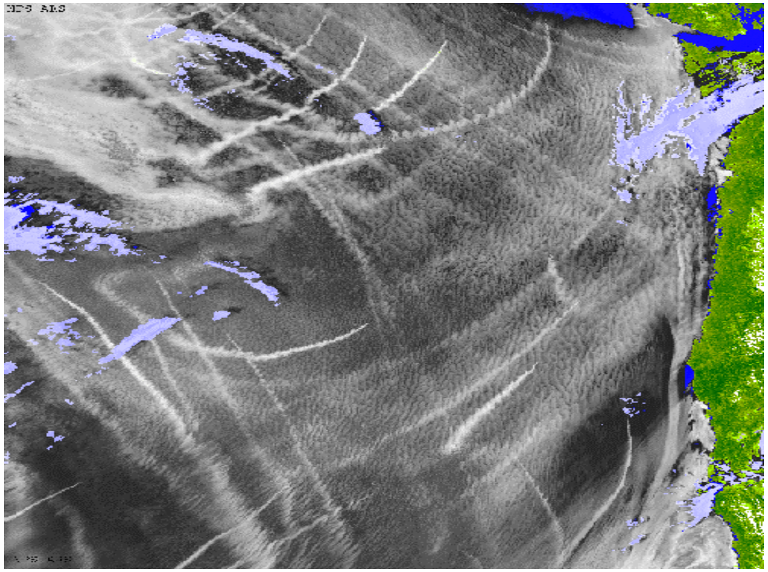
Effect of Added CCN

(Cloud Condensation Nuclei)

- Adding CCN makes clouds with more, smaller droplets.
- These clouds are whiter, reflect more sunlight
- Too many tiny CCN suppress coalescence and precipitation

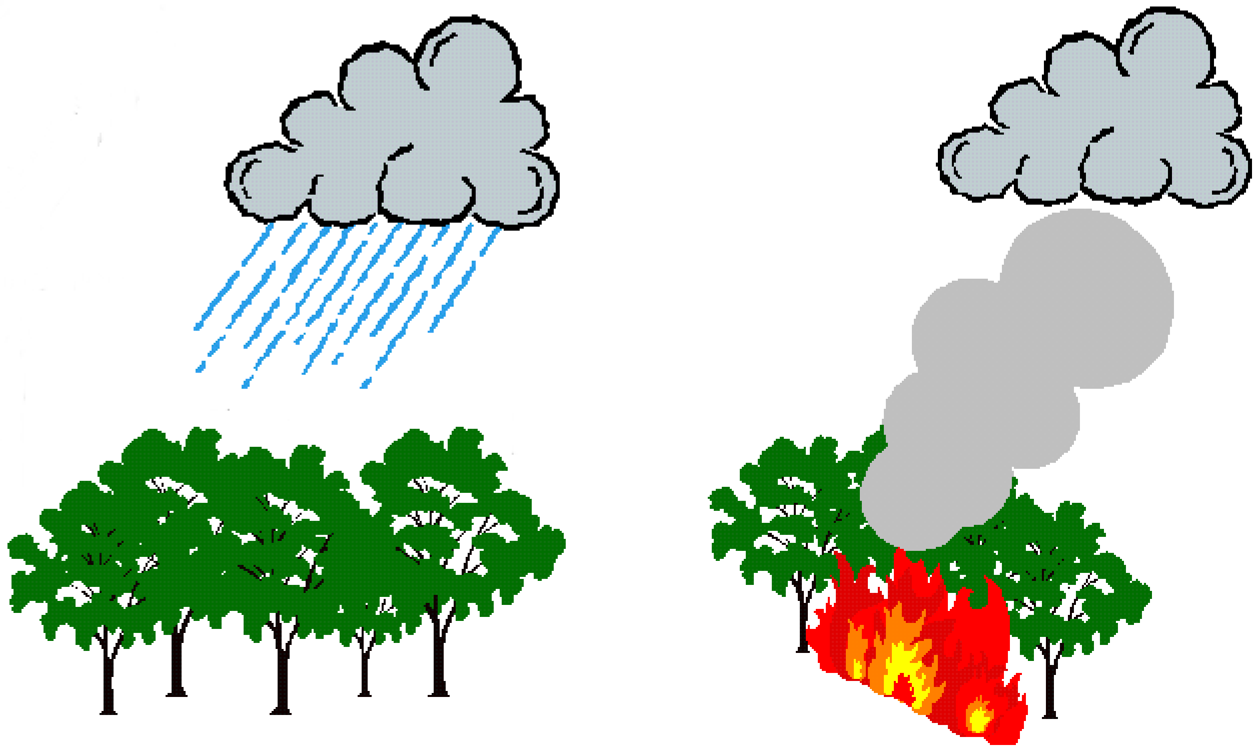


Industrial pollution tracks over Manitoba, Canada

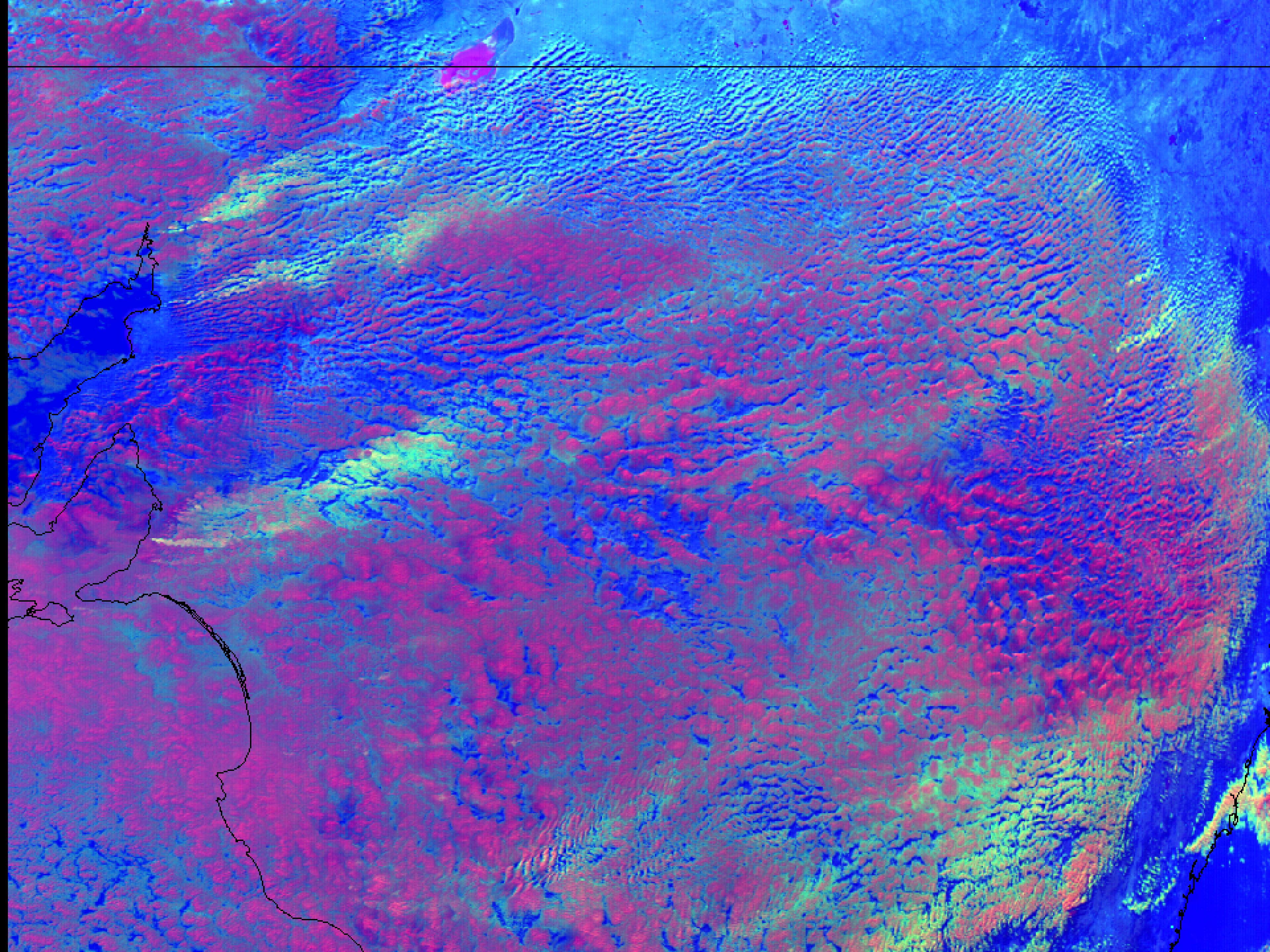


Ship tracks off the Washington coast

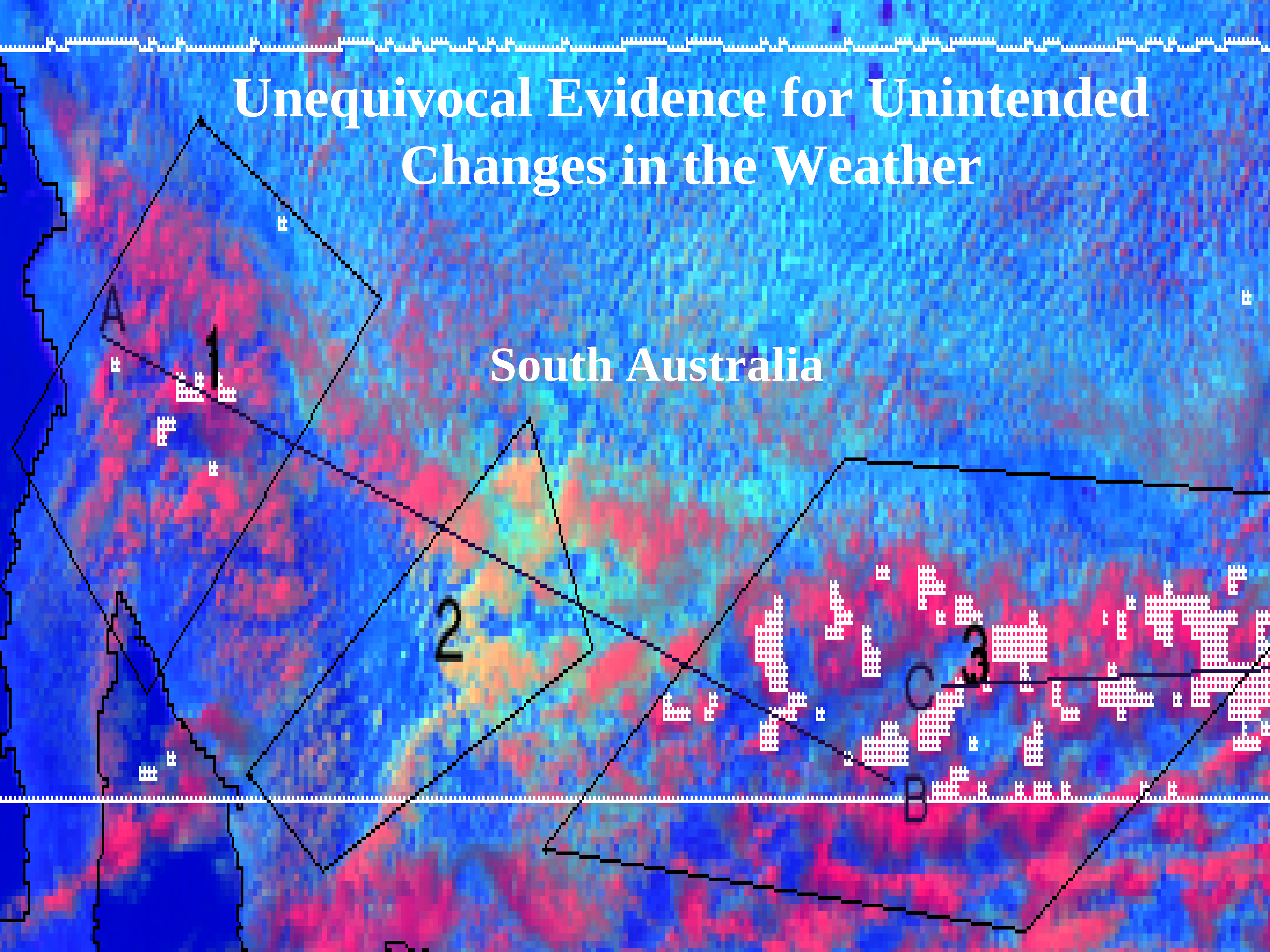
Tropical Rainfall Measuring Mission (TRMM) satellite observations show how rain is inhibited in clouds forming in dirty air, i.e., air containing many small CCN, contributed by aerosol particles such as smoke, air pollution and desert dust.



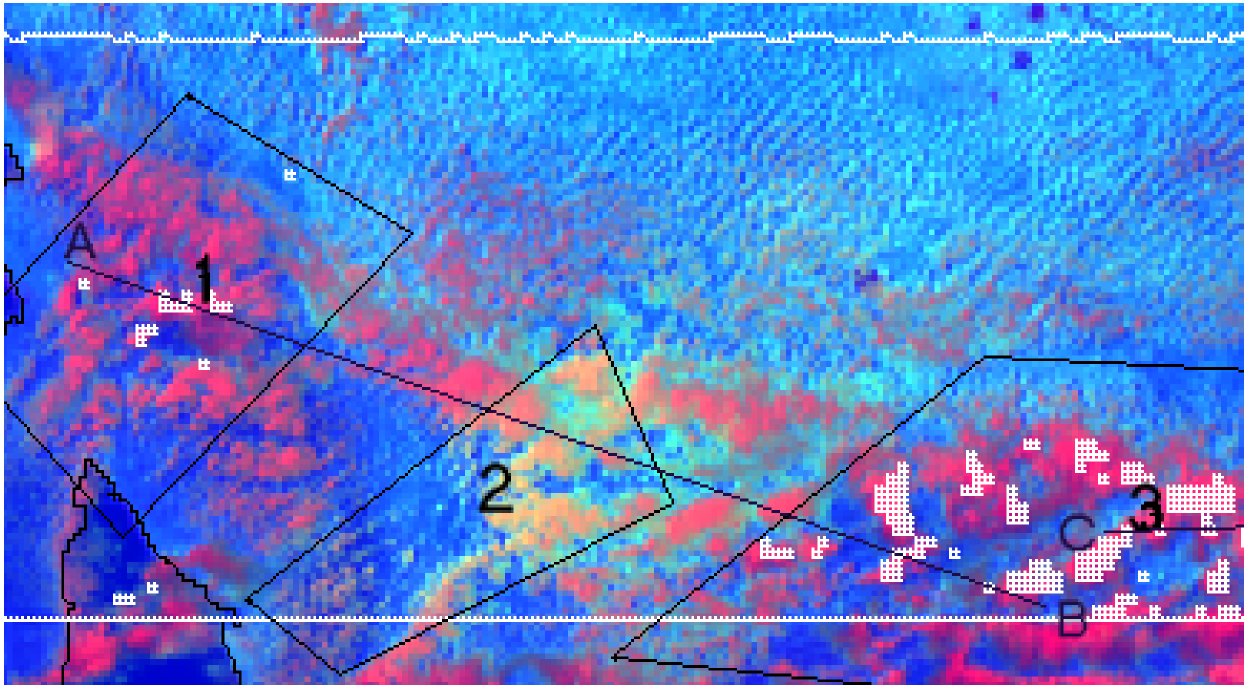
Rosenfeld D., 1999: TRMM Observed First Direct Evidence of Smoke from Forest Fires Inhibiting Rainfall. *Geophysical Research Letters*. **26,** (20), 3105-3108.



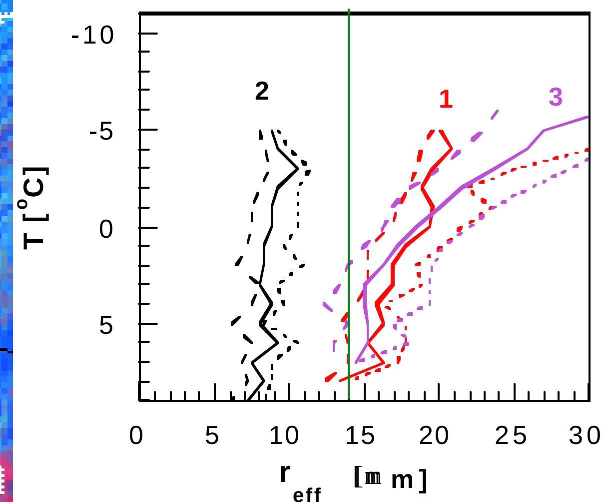
Unequivocal Evidence for Unintended Changes in the Weather



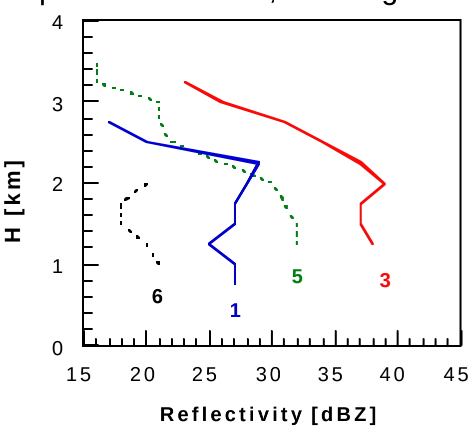
Suppression of Rain and Snow by Urban and Industrial Air Pollution (Rosenfeld, 2000, Science)



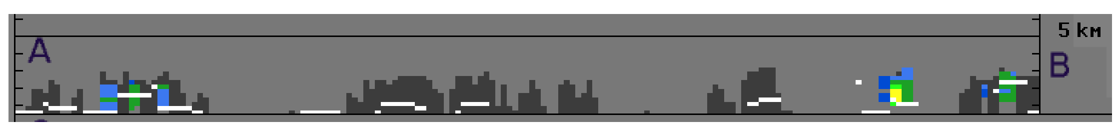
VIRS painting yellow pollution tracks in the clouds over South Australia, due to reduced droplets size. PR shows precipitation as white patches only outside the pollution tracks, although clouds have same depth.

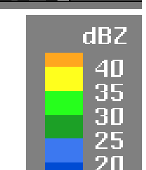


VIRS retrieved effective radius does not exceed the 14 μm precipitation threshold in polluted clouds within area 2 in the Australia image.

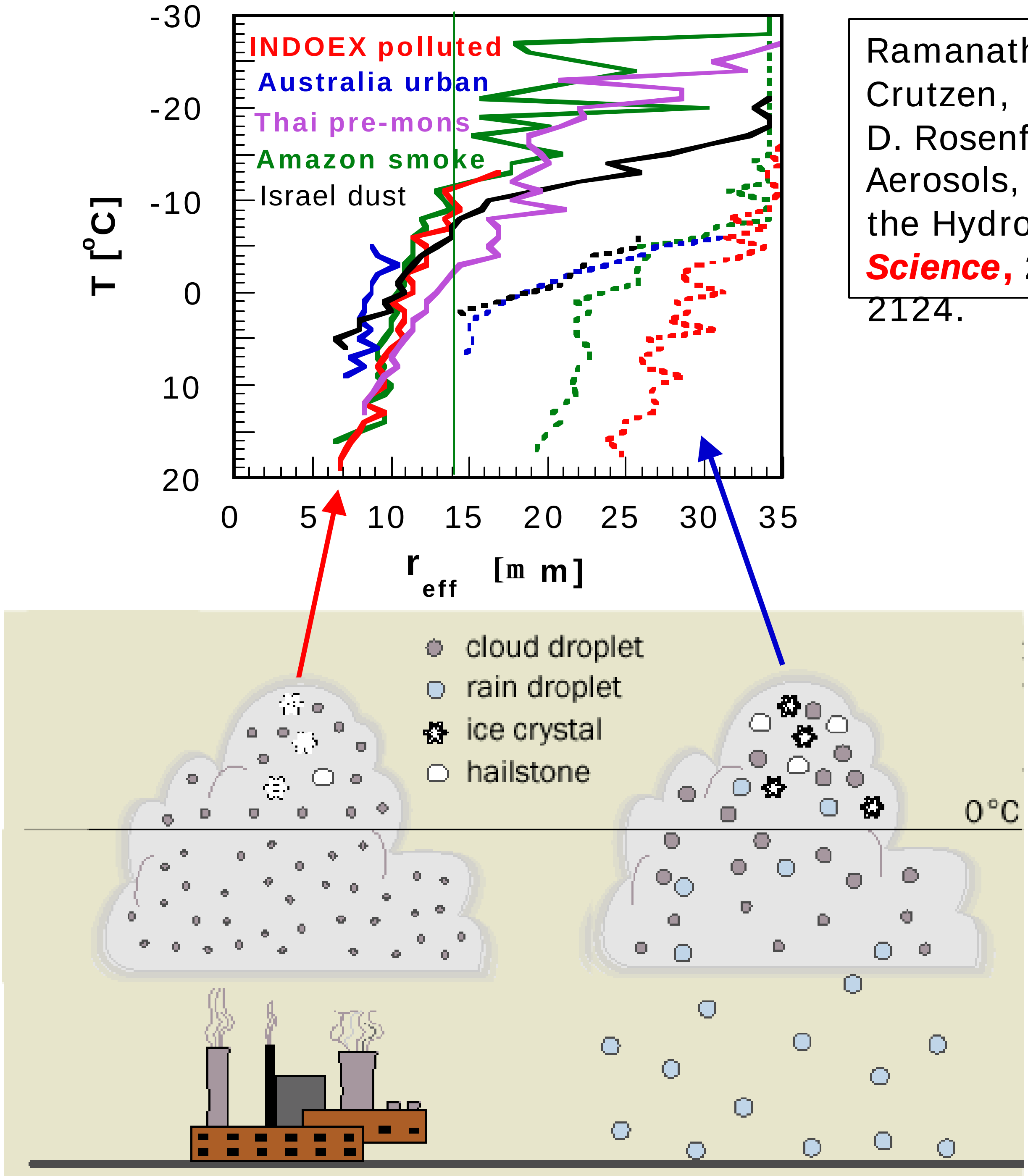


PR shows bright band in clean clouds. Therefore, pollution suppressed rain and snow in polluted clouds.





TMI shows ample water in the polluted clouds



Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld, 2001: Aerosols, Climate and the Hydrological Cycle. ***Science*, 294**, 2119-2124.

Rocky Mountains, CO

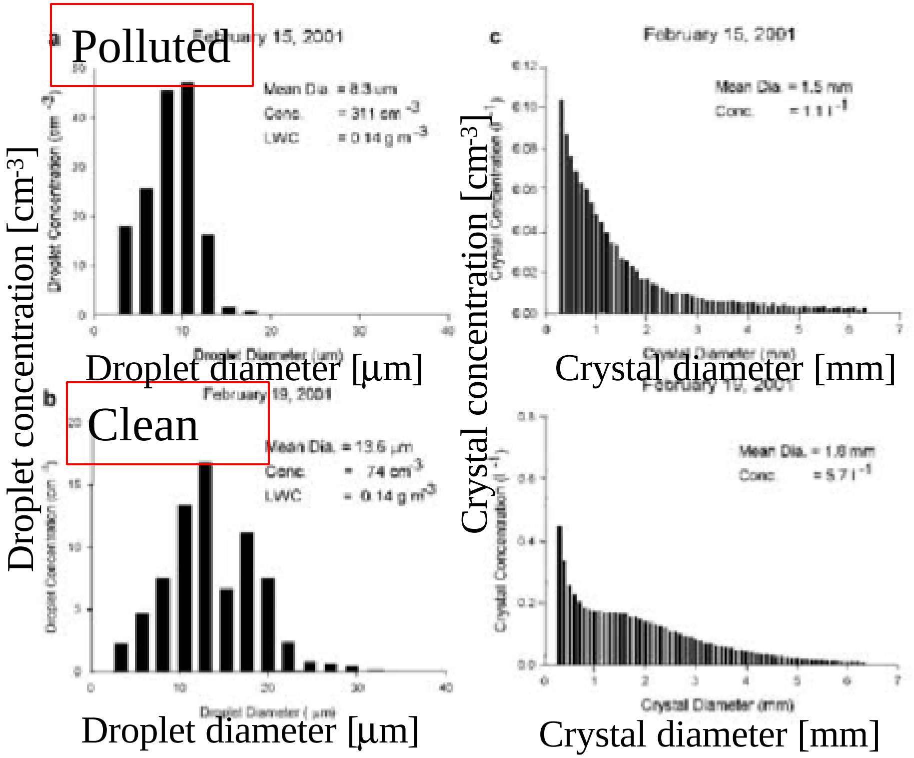


Figure 4. Cloud droplet and snow size spectra for the sampling periods on Feb. 15 and 19, 2001.

Table 1. Chemical and Physical Properties of Cloud Droplets and Snow During Two Precipitation Events

February	15	19
Major Habit	Planar Dendrite	Planar Dendrite
Rime Category	Unrimed (0.5)	Moderate (2.0)
Rime Mass Frac.	5%	51%
SPL Precip. Rate	0.02 mm hr^{-1}	0.38 mm hr^{-1}
ISS Precip.Rate	0 to 0.1 mm hr^{-1}	1.1 mm hr^{-1}
SPL Temperature	−13°C	−4°C
Snow δ^{18}O	−22.1	−16.5
Cloud δ^{18}O	−21.1	−16.2
δ^{18}O Snow Mass Temp. Of Origin	−14°C	−4.8°C
Cloud Top Temp	−19°C	−22°C
Snow CAE $SO_4^=$	0.011 µg m^{-3}	0.072 µg m^{-3}
Cloud CAE $SO_4^=$	1.1 µg m^{-3}	0.12 µg m^{-3}
Droplet Mean Dia.	8.3 mm	13.6 mm
Droplet Conc.	310 cm^{-3}	74 cm^{-3}
Cloud SCLW	0.13 g m^{-3}	0.14 g m^{-3}

on Feb. 15 and 19 were 0.02 mm hr^{-1} and 0.38 mm hr^{-1}, respectively.

The difference between the cloud clear air equivalent anthropogenic aerosol sulfate concentrations on the two days is nearly an order of magnitude, but in absolute terms it is **only 1 mg m^{-3}. Astonishingly, this small amount of aerosol can reduce the snowfall rate up to 50%.**

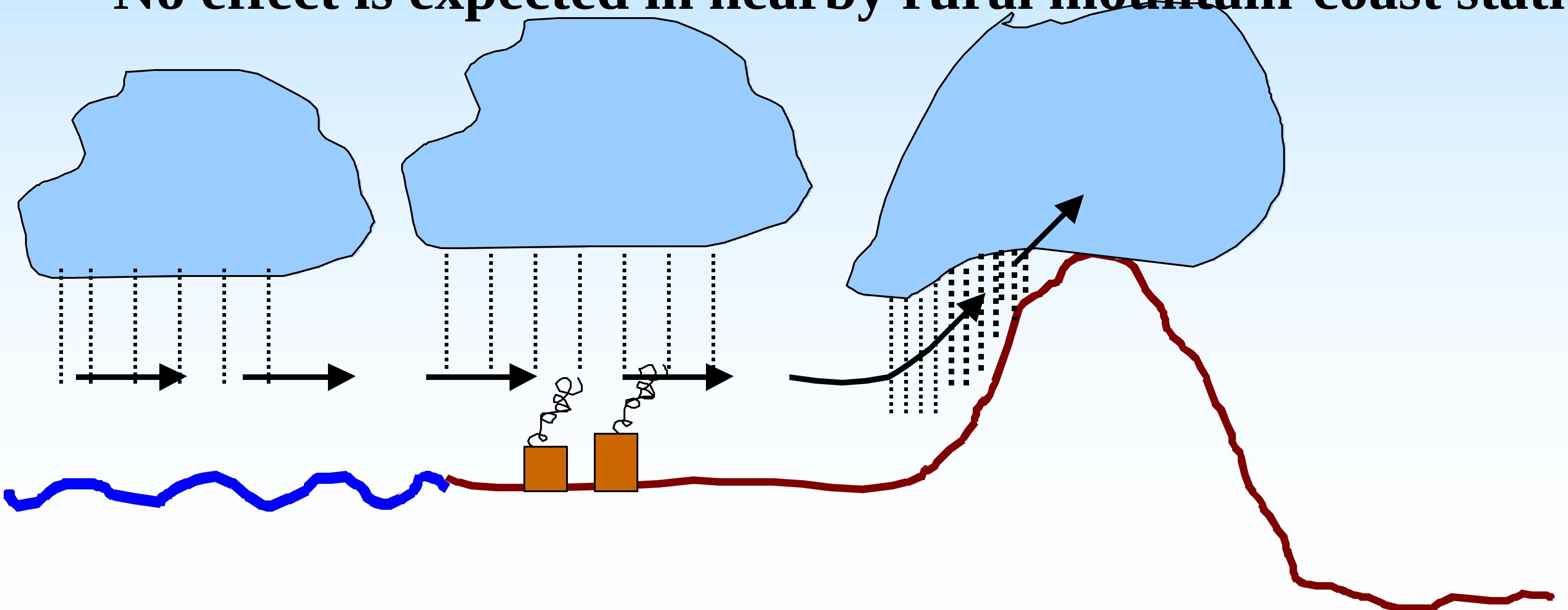
Evidence is presented to demonstrate the possible magnitude of the secondary indirect aerosol effect on precipitation rates from cold mixed-phase clouds in mountainous regions where a seeder-feeder cloud couplet is present. Changes as small as 1 µg m^{-3} in CCN aerosol concentration can cause significant changes in cloud properties and precipitation efficiencies. (Quoted from Borys et al., GRL 2003).

The study purposes:

- Quantify the effects of air pollution on precipitation downwind of major urban areas
- Determine the conditions in which the pollution effects are mostly effective

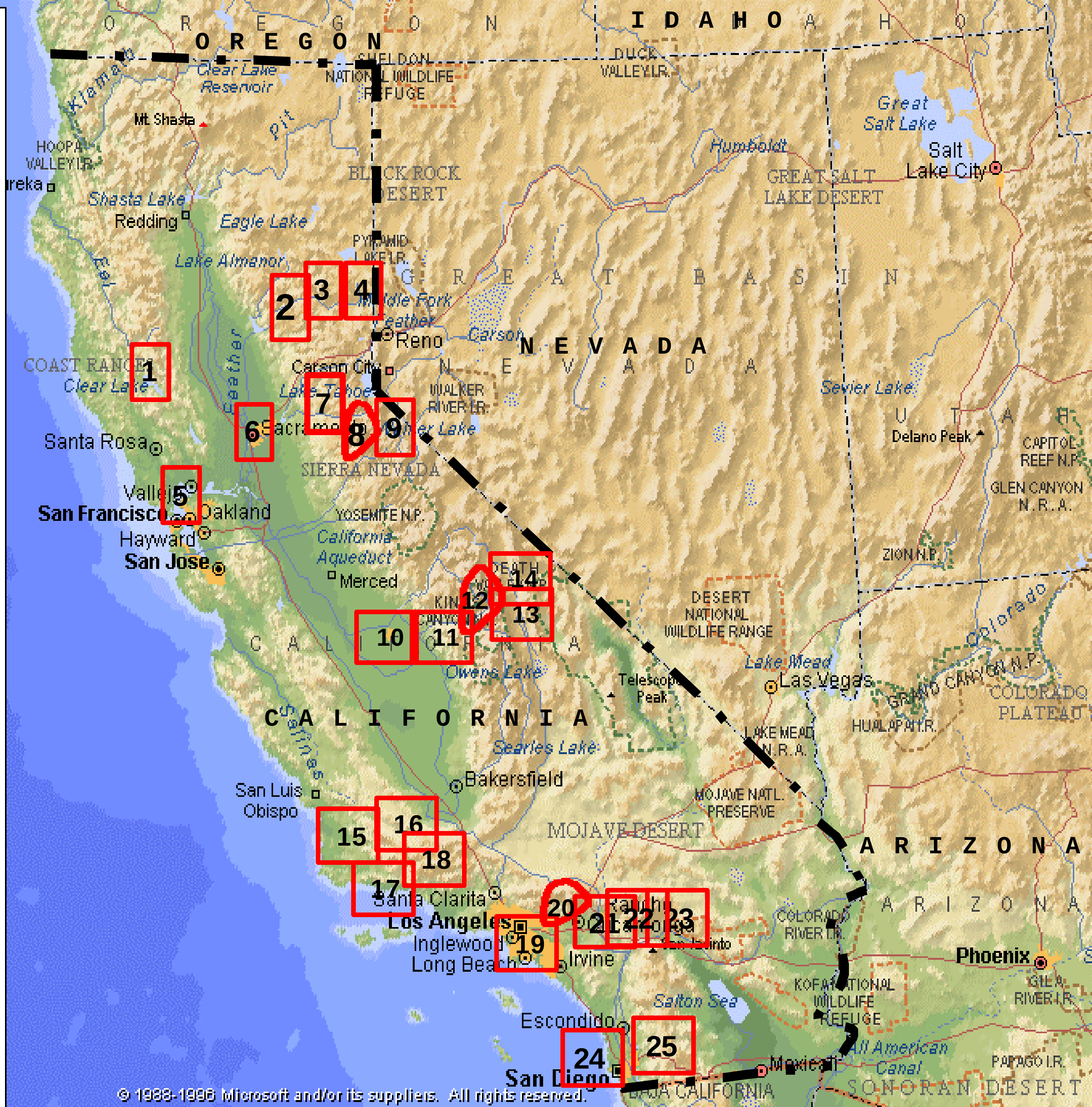
The study principles:

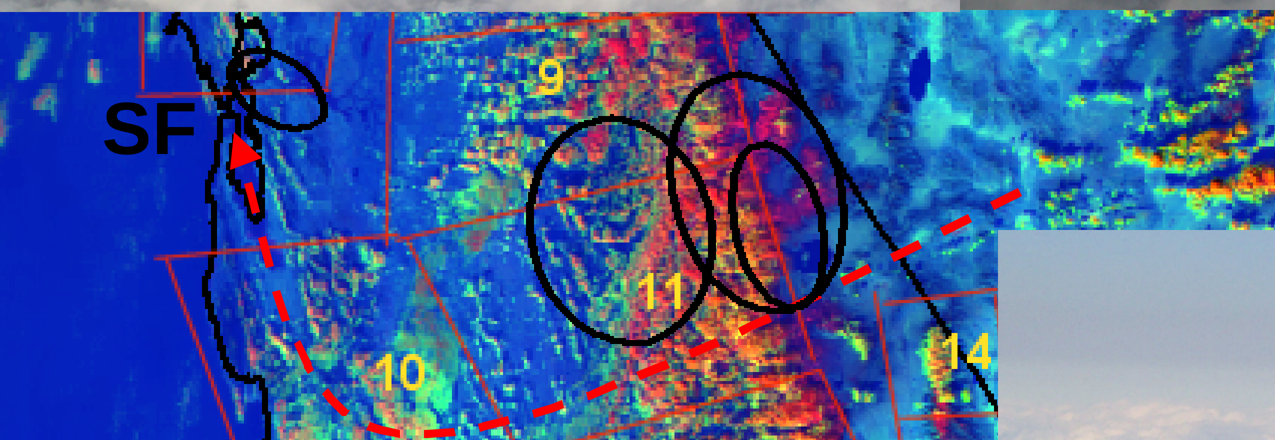
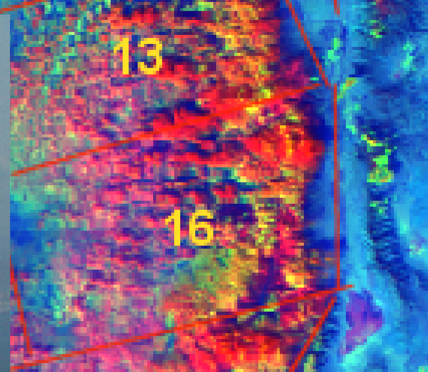
- The effect will be shown best where maritime air is polluted over coastal urban areas, and the polluted air rises over mountains downwind and forms new polluted clouds.
- The effect will be manifested as a reduction of the orographic enhancement factor with respect to the upwind coastal rainfall.
- The effect is most detectable in highly correlated mountain and coastal rain stations.
- No effect is expected in nearby rural mountain-coast stations.



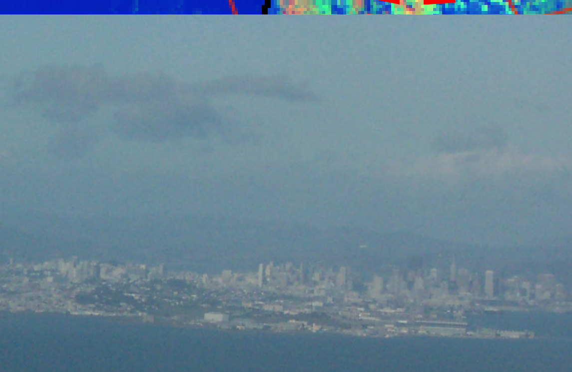
Legend

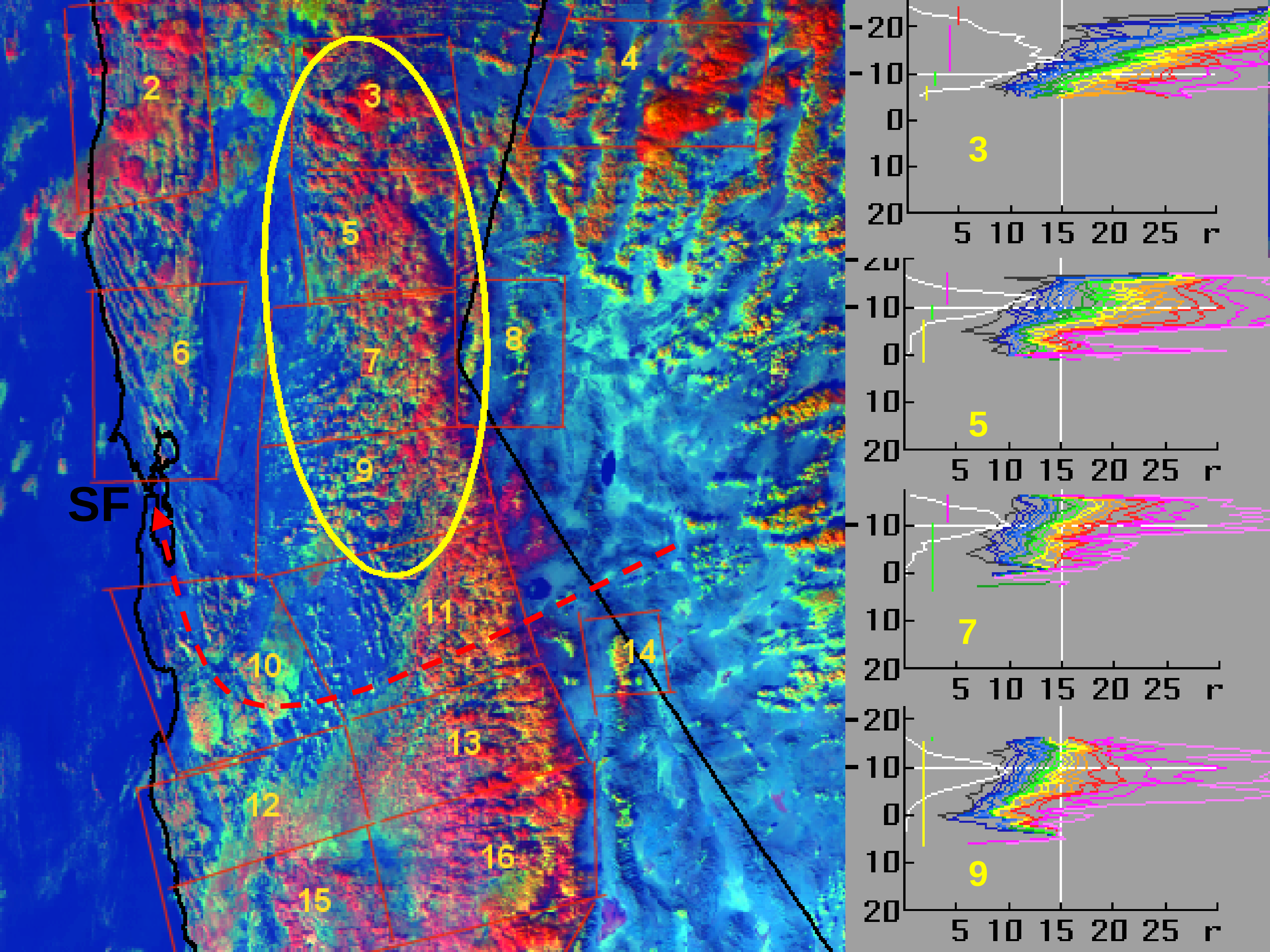
1E. Ukiah
2E. Lake Spaulding
3E. Bowman
4E. Boca
5A. San Francisco
6A. Sacramento
7A. Pacific House
8A. Cluster of snow packs in the divide line downwind to Sacramento
9A.Woodfords
10B. Fresno
11B. Grant Grove
12B. Cluster of snow packs in the divide line downwind to Fresno
13B. Glacier
14B. Bishop Lake
15F. Lompoc
16F. Mt. Figuroa
17F. Santa Barbara
18F. Mt. pine
19C. Los Angeles area
20C. Cluster of stations downwind to Los Angeles
21C. Lake Arrowhead
22C. Big Bear Lake
23C. Morongo
24. San Diego
25. Cuyamaca



MODIS AQUA
7 Dec 2003, 12:50 PST





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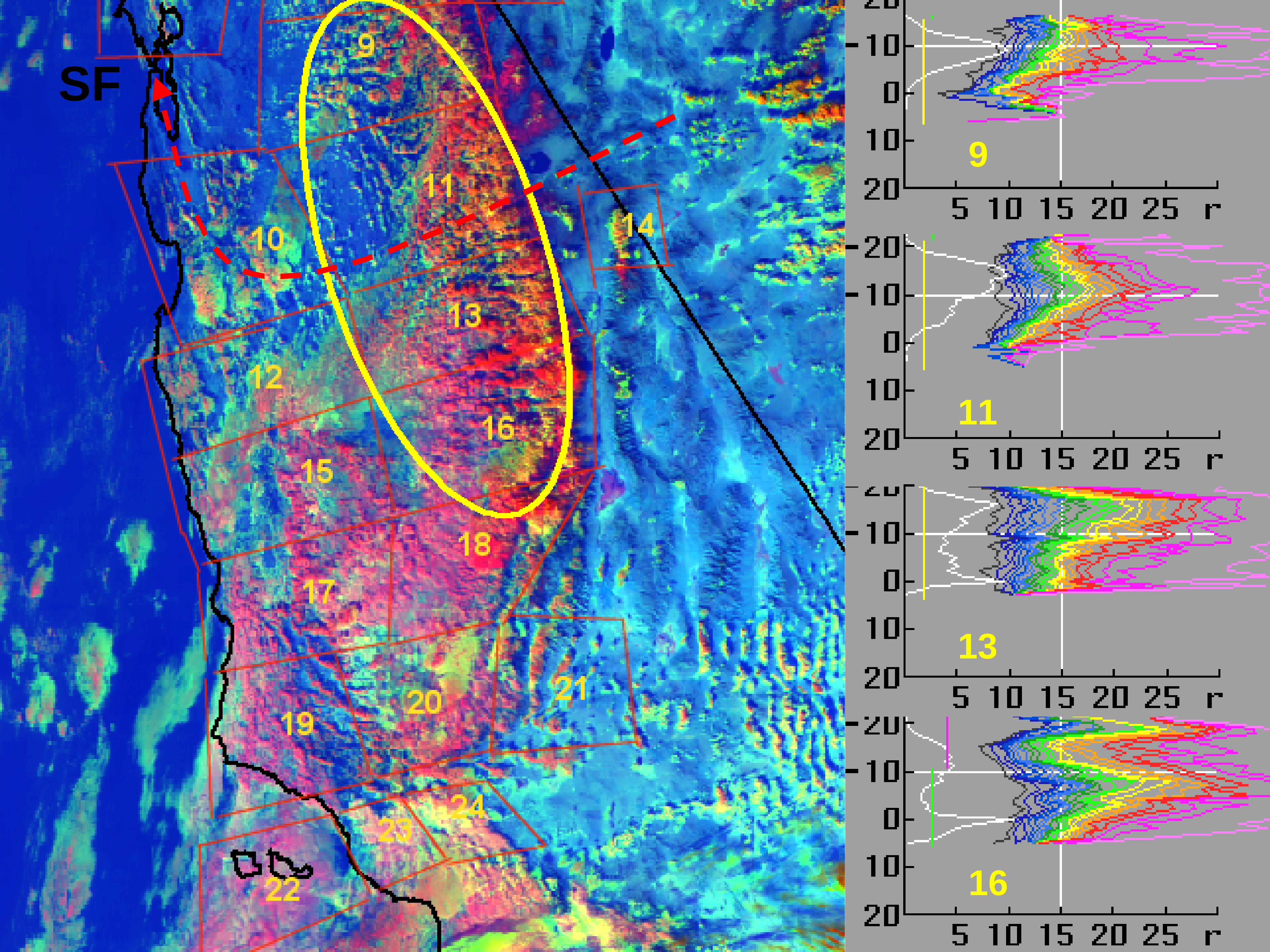

SF
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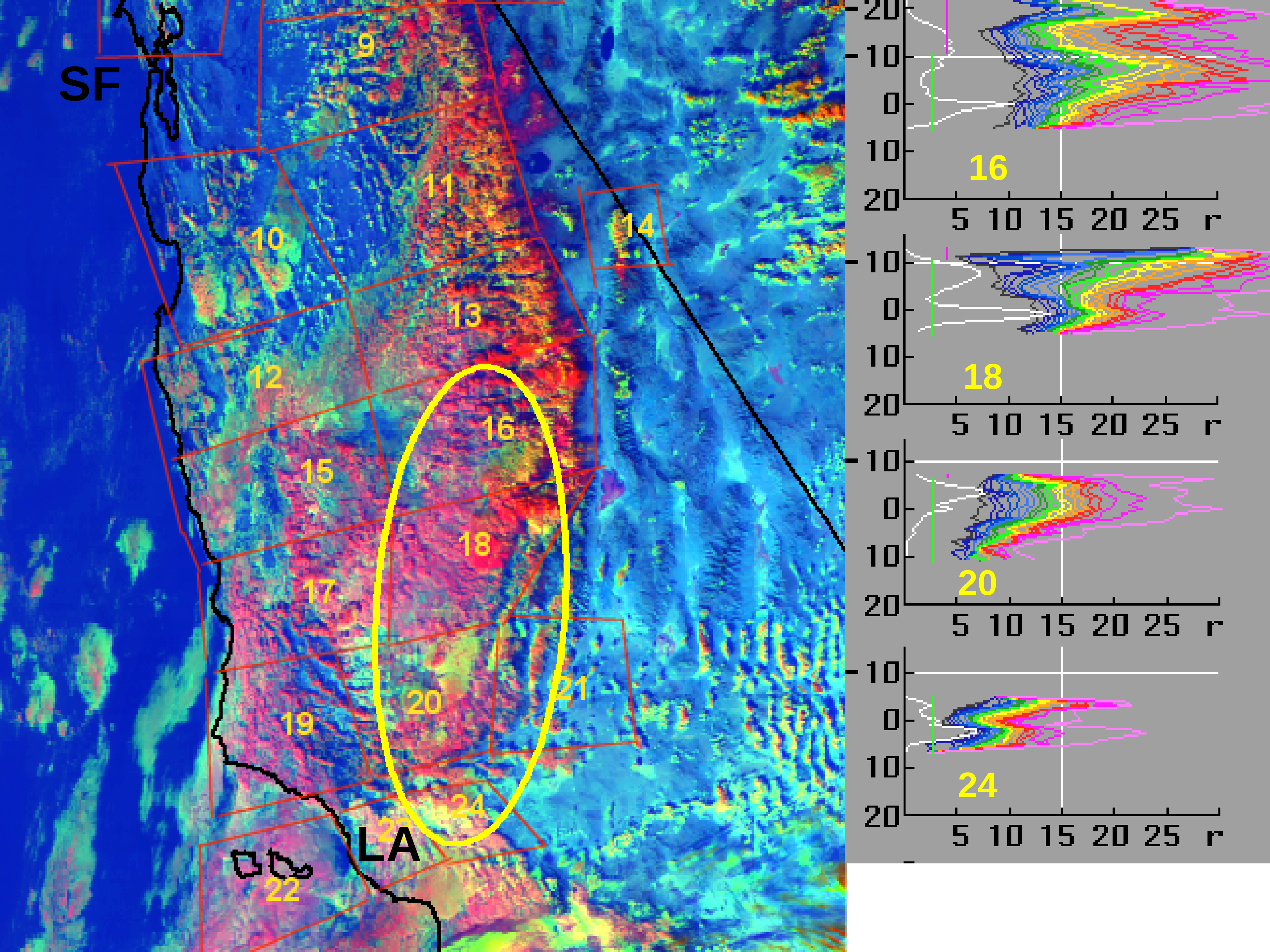

SF
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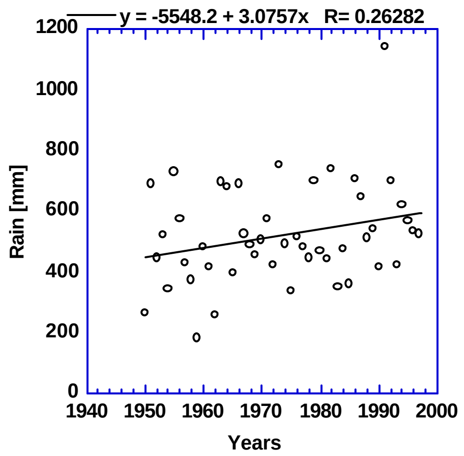
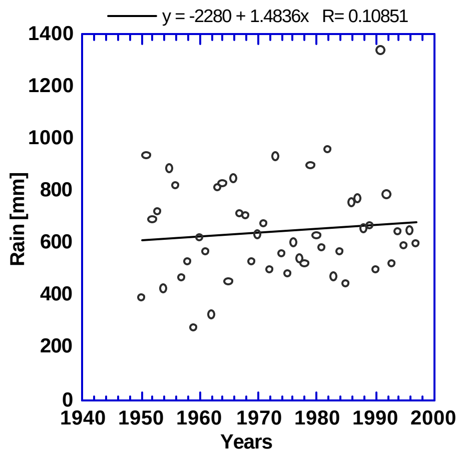
Why use the ratio between two stations?

Both the plain (Israel central coast) and the Hill stations (Judea Hills) show an increase in the yearly rain amounts

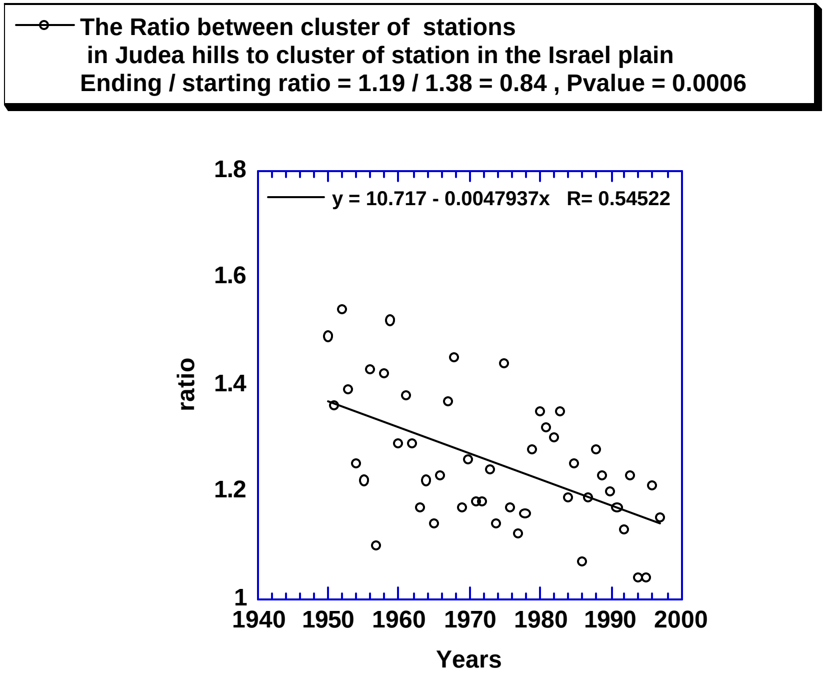
Yearly avarage rain - Cluster of stations in Israel internal Plain



Yearly avarage rain - Cluster of stations in Judea hills



But the ratio (the orographic component of the precipitation) between the hill to the plain stations is decreasing!



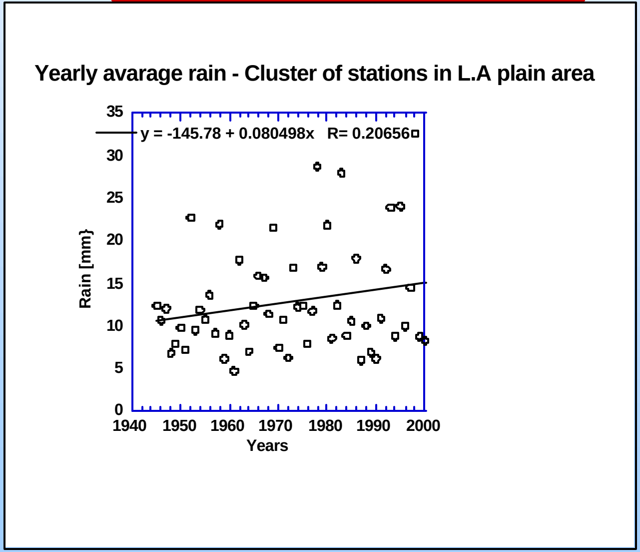
Same thing happens in southern California : The plains and the Hill stations show an increase in the yearly rain amounts

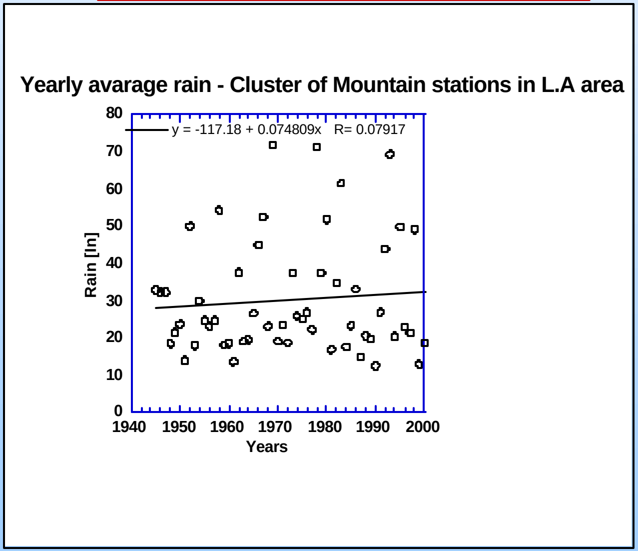
Plain stations:

Los Angeles 355, Los Angeles CC, Pomona, Los Angeles AP, Beverly Hills 22 , Chino, San Bernardino

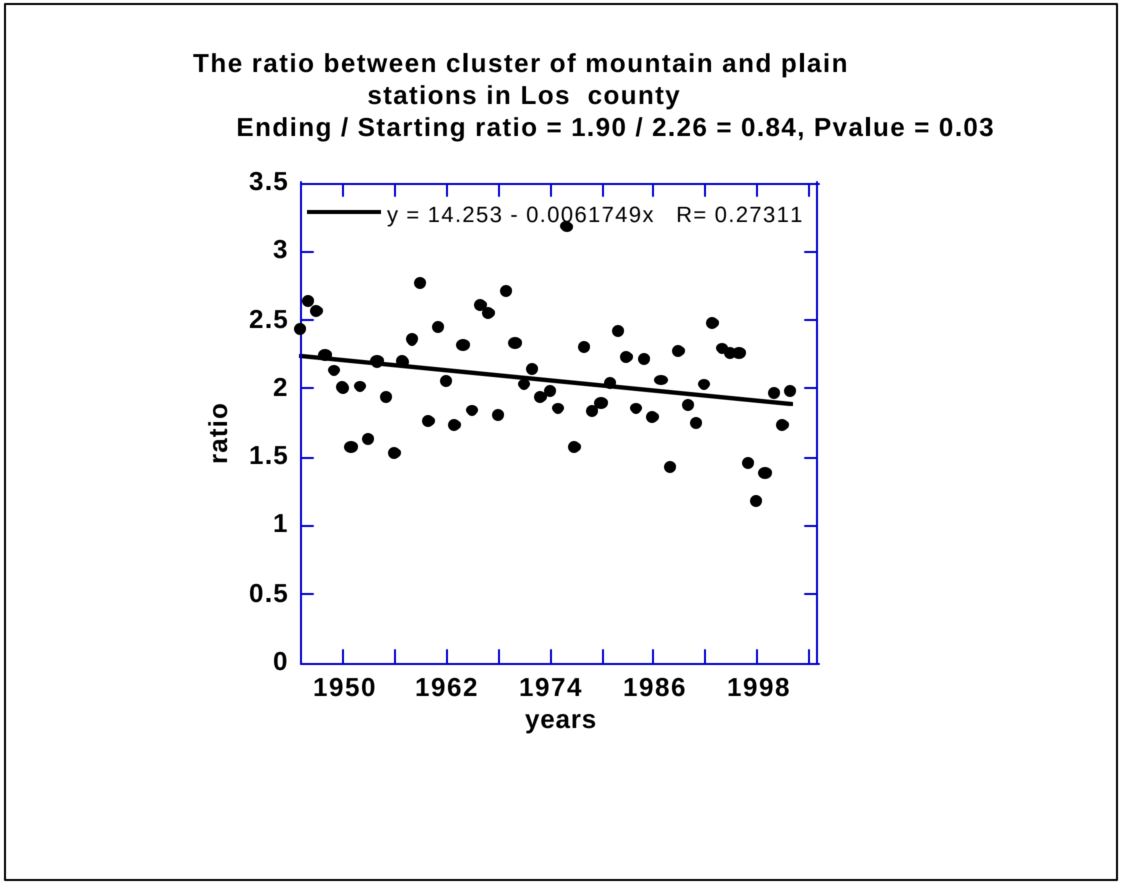
Mountain stations:

Lake Arrowhead, Sierra PH, RaywoodFlats, Crystal





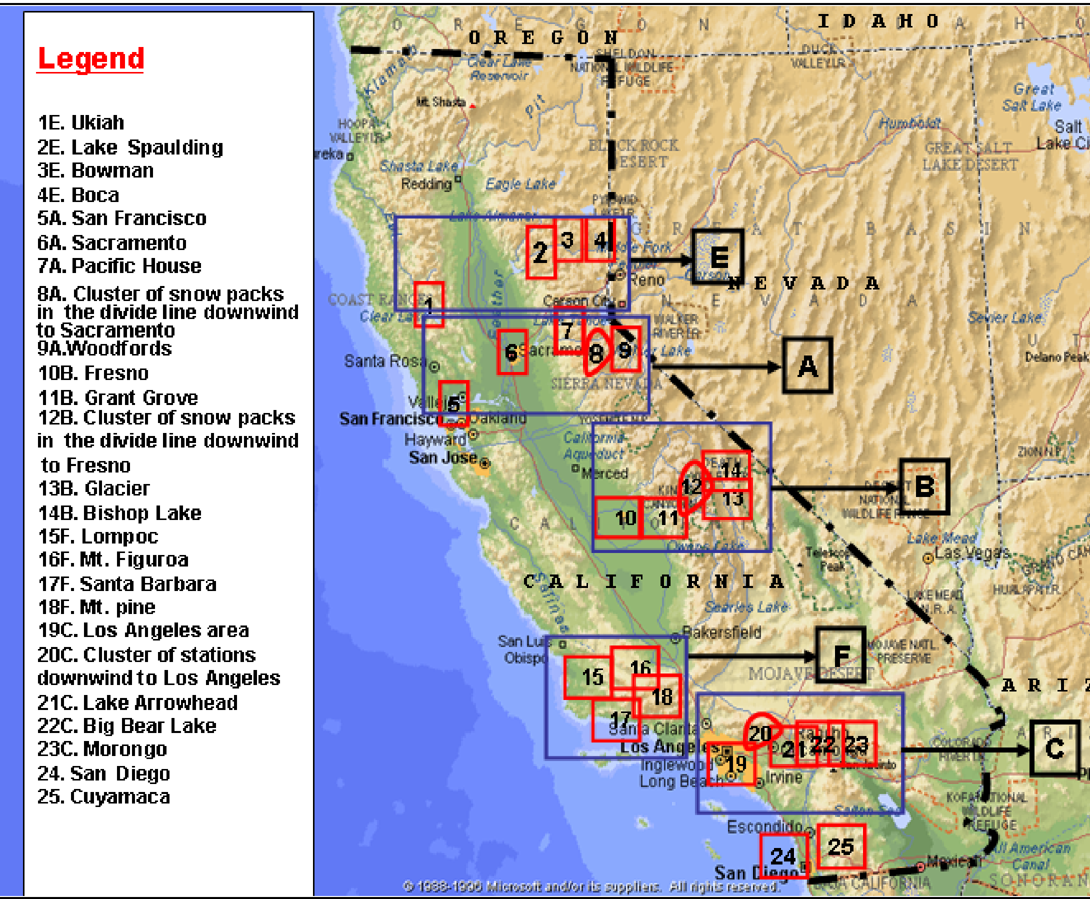
But the ratio between the mountain and the plains stations is decreasing



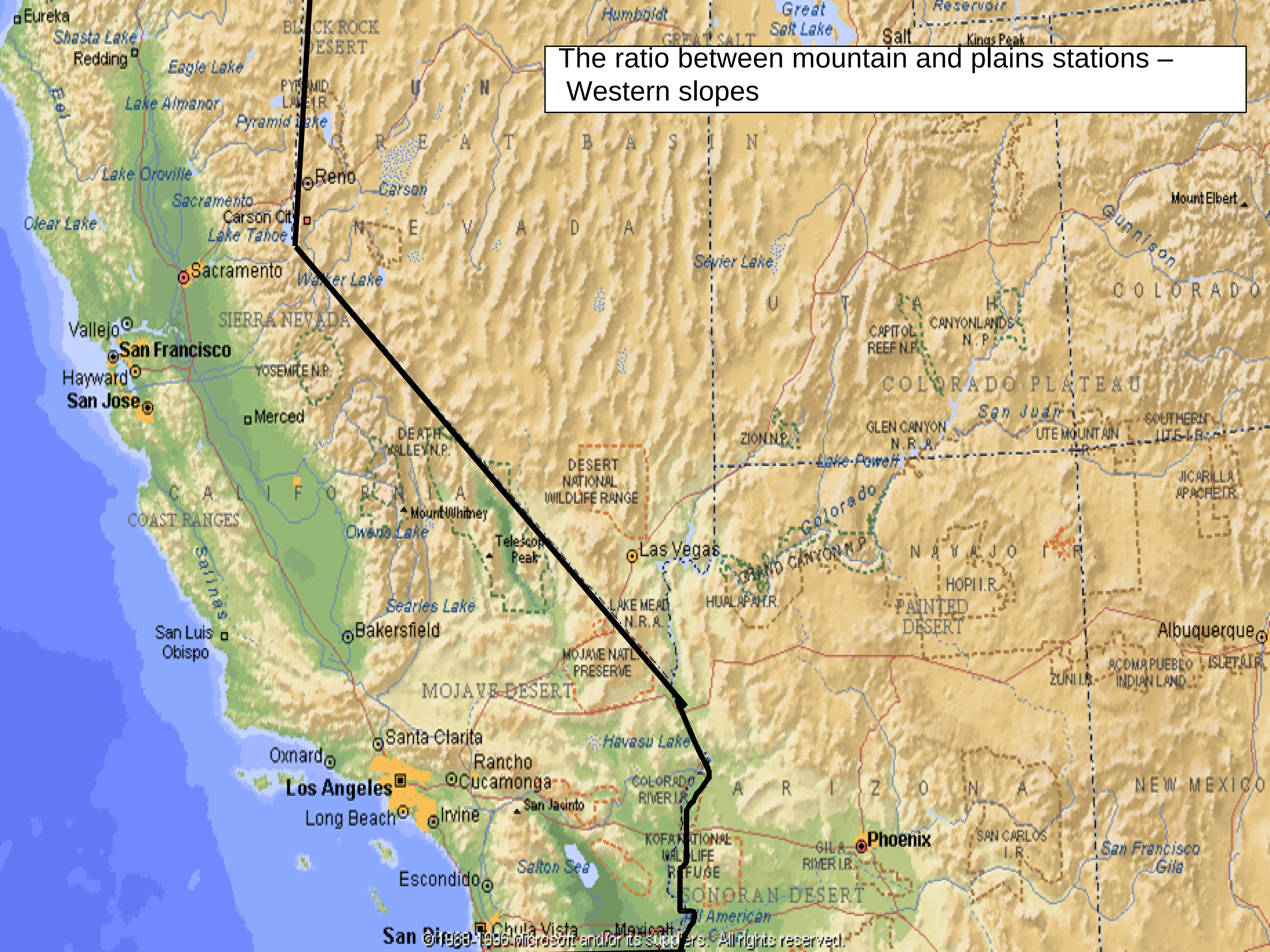
The study areas :

California coastal range and the Sierra Nevada

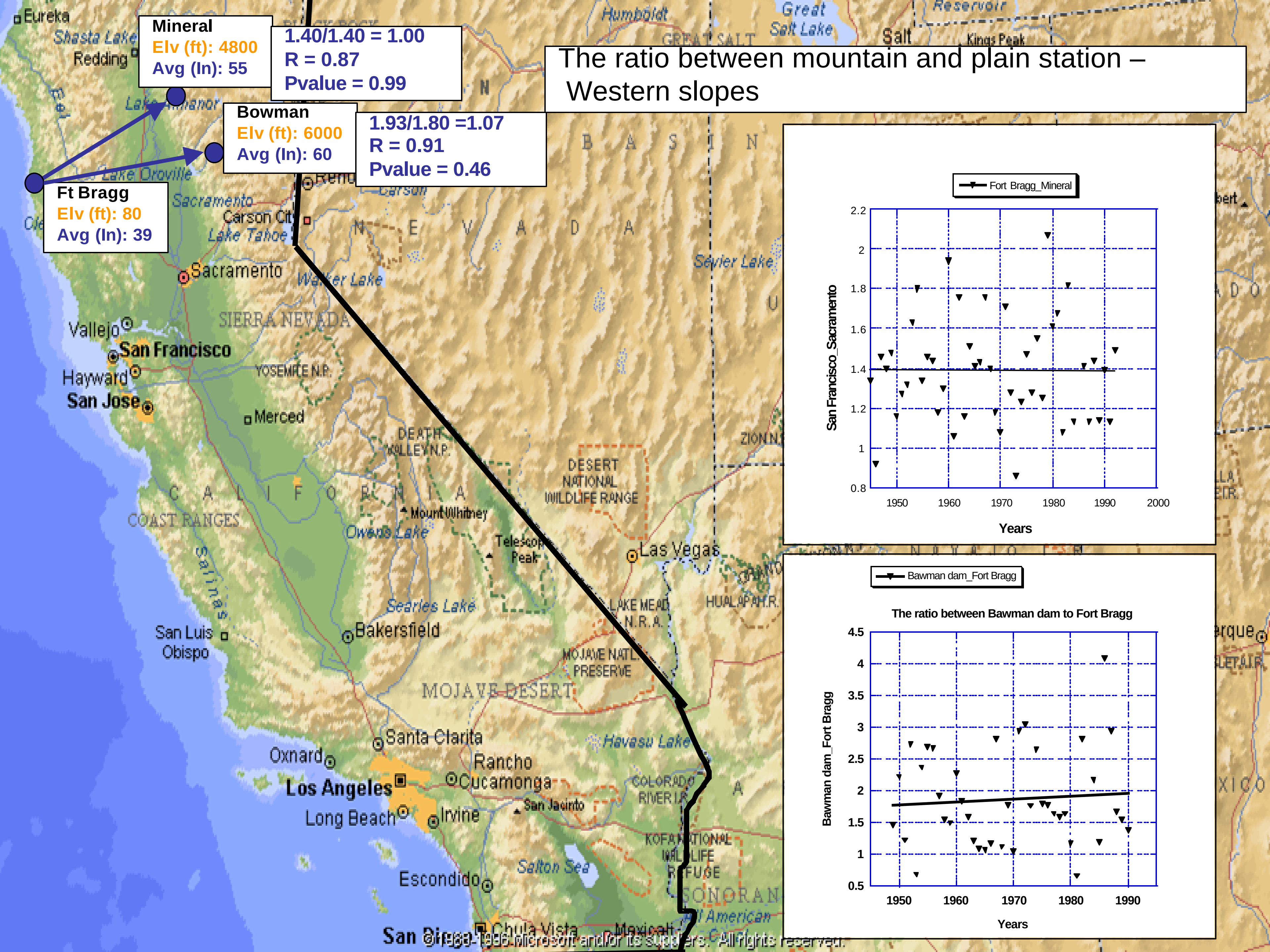
Israel central mountain range



The ratio between mountain and plains stations – Western slopes



The ratio between mountain and plain station – Western slopes



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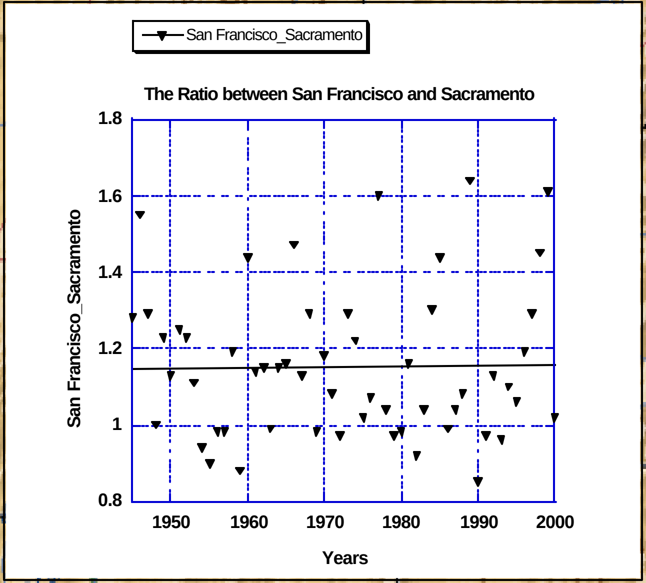
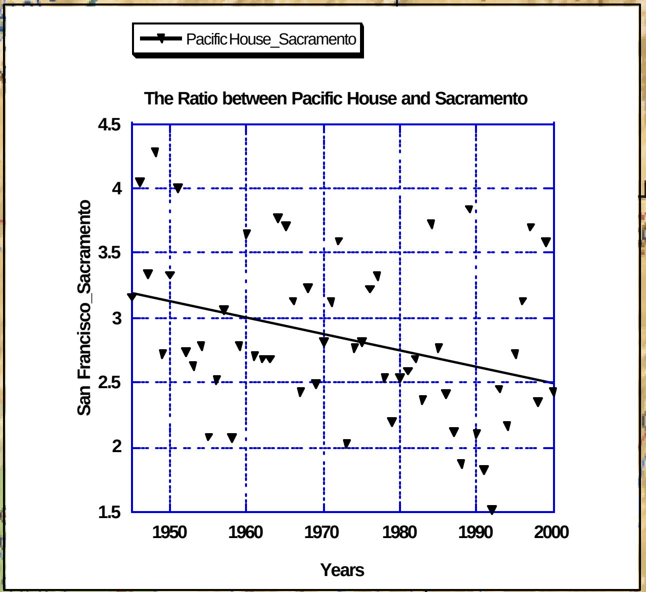
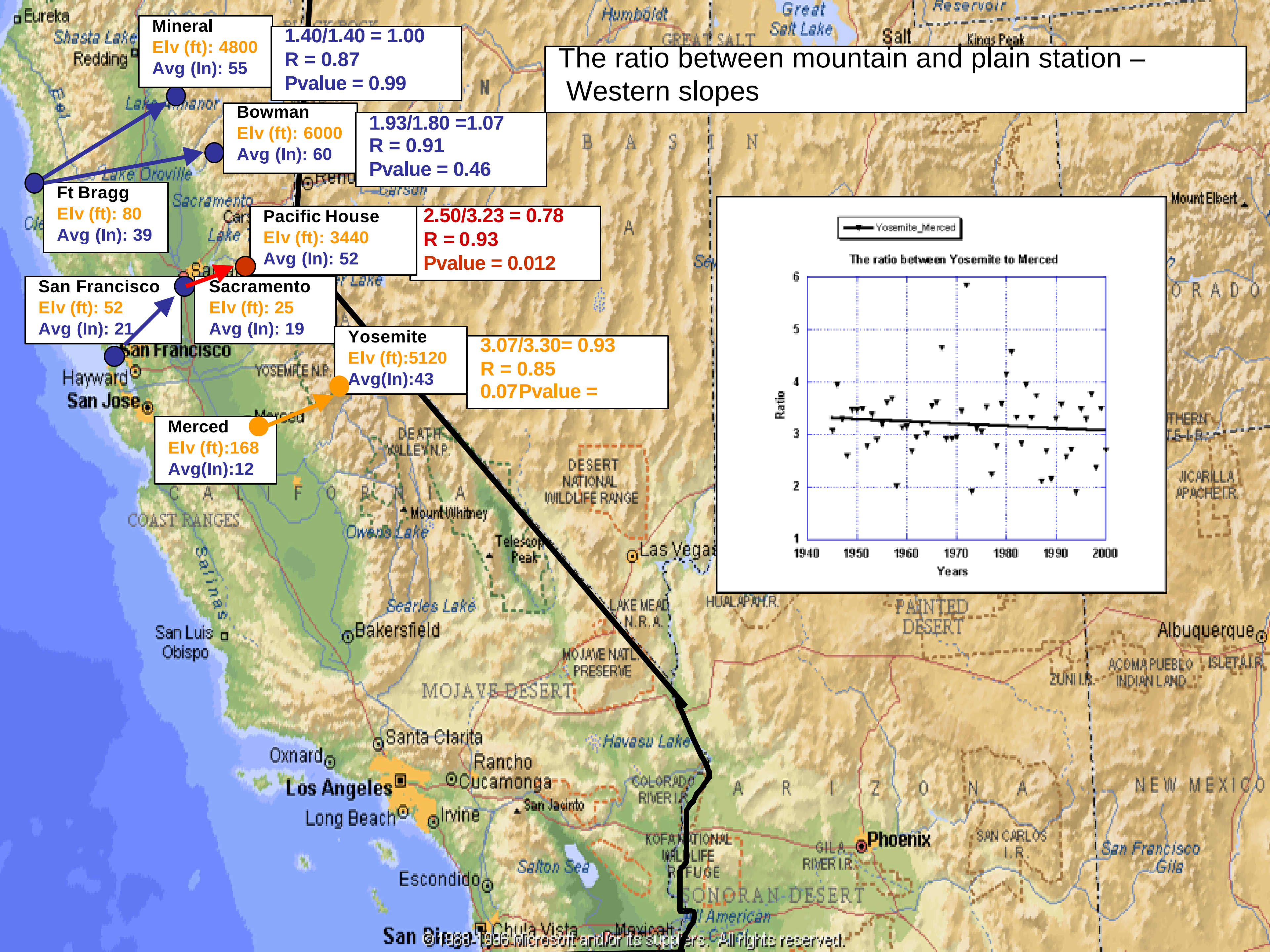




The ratio between mountain and plain station – Western slopes



The ratio between mountain and plain station – Western slopes

Mineral
Elv (ft): 4800
Avg (In): 55

1.40/1.40 = 1.00
R = 0.87
Pvalue = 0.99

Bowman
Elv (ft): 6000
Avg (In): 60

1.93/1.80 =1.07
R = 0.91
Pvalue = 0.46

Ft Bragg
Elv (ft): 80
Avg (In): 39

Pacific House
Elv (ft): 3440
Avg (In): 52

2.50/3.23 = 0.78
R = 0.93
Pvalue = 0.012

San Francisco
Elv (ft): 52
Avg (In): 21

Sacramento
Elv (ft): 25
Avg (In): 19

Yosemite
Elv (ft):5120
Avg(In):43

3.07/3.30= 0.93
R = 0.85
0.07Pvalue =

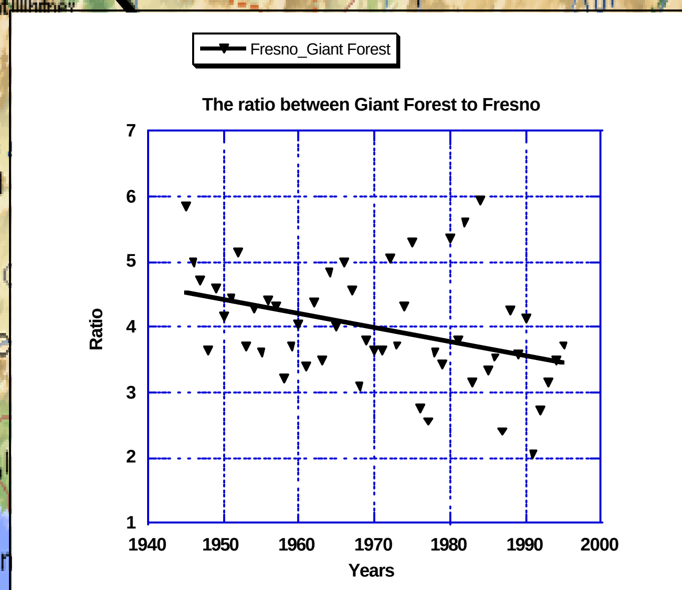
Merced
Elv (ft):168
Avg(In):12

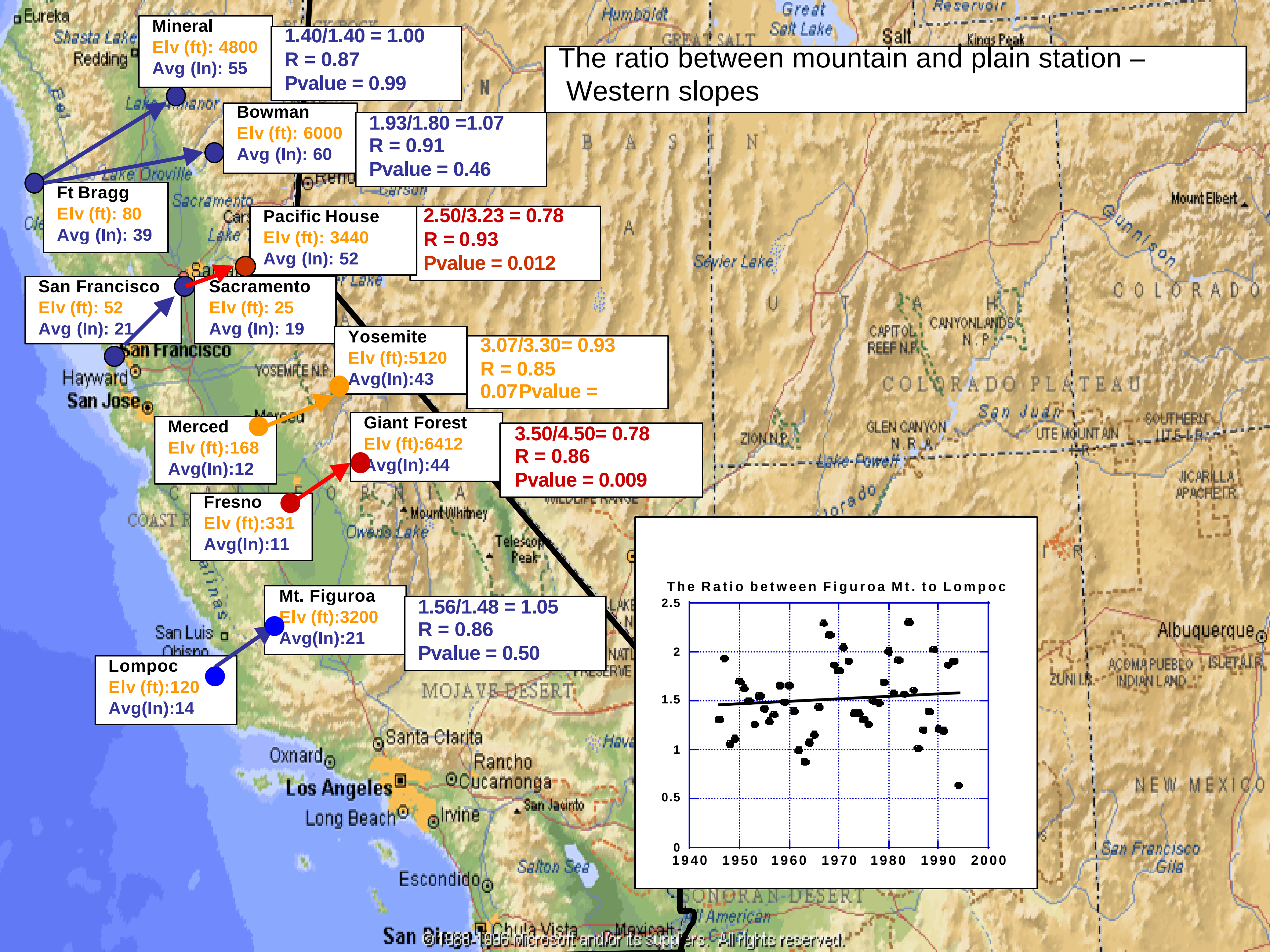
Giant Forest
Elv (ft):6412
Avg(In):44

3.50/4.50= 0.78
R = 0.86
Pvalue = 0.009

Fresno
Elv (ft):331
Avg(In):11

Sequoia-kings N.P :The 4th polluted park in The U.S According to the NPCA

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Fresno
Elv (ft):331
Avg(In):11
Mt. Figuroa
Elv (ft):3200
Avg(In):21
1.56/1.48 = 1.05
R = 0.86
Pvalue = 0.50
Lompoc
Elv (ft):120
Avg(In):14
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The Ratio between Figuroa Mt. to Lompoc
2.5
2
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1940
1950
1960
1970
1980
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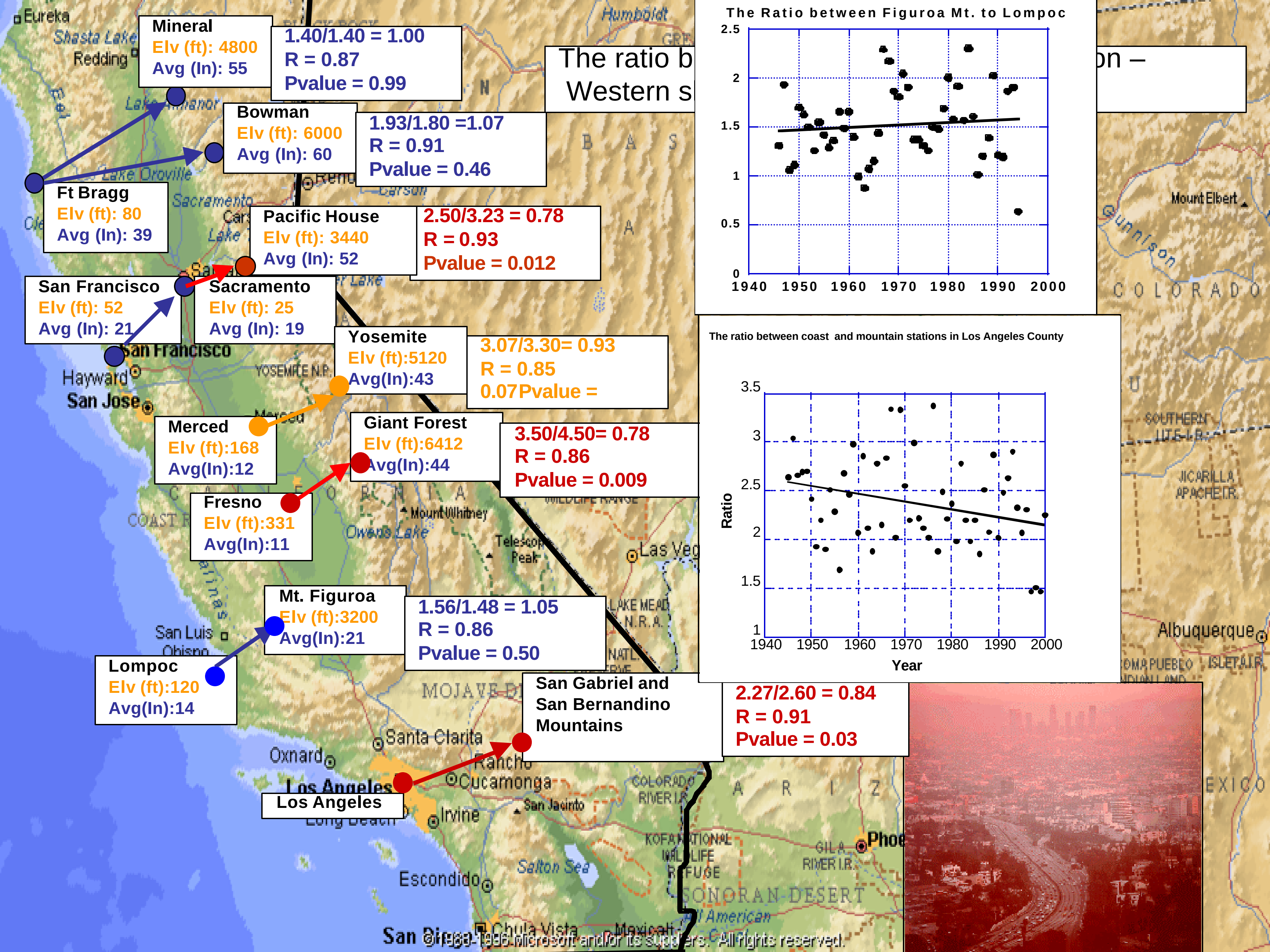
2000



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R = 0.86
Pvalue = 0.50
Lompoc
Elv (ft):120
Avg(In):14
San Gabriel and
San Bernandino
Mountains
2.27/2.60 = 0.84
R = 0.91
Pvalue = 0.03
Los Angeles
The Ratio between Figuroa Mt. to Lompoc
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1.5
1
0.5
0
1940 1950 1960 1970 1980 1990 2000
The ratio between coast and mountain stations in Los Angeles County
Ratio
3.5
3
2.5
2
1.5
1
1940 1950 1960 1970 1980 1990 2000
Year
Eureka
Shasta Lake
Redding
Lake Almanor
Lake Oroville
Sacramento
San Francisco
Hayward
San Jose
Merced
Mount Whitney
Owens Lake
Telescope Peak
Las Veg
San Luis Obispo
MOJAVE
Santa Clarita
Oxnard
Los Angeles
Rancho Cucamonga
Irvine
San Jacinto
Salton Sea
Escondido
Chula Vista
San Diego
Albuquerque
Mount Elbert
Gunnison
COLORADO
SOUTHERN UTE I.R.
JICARILLA APACHE I.R.
SONORAN DESERT
KOFA NATIONAL WILDLIFE REFUGE
GILA RIVER I.R.
Phoe
COLORADO RIVER I.R.
LAKE MEAD N.R.A.
ARIZ
EXICO
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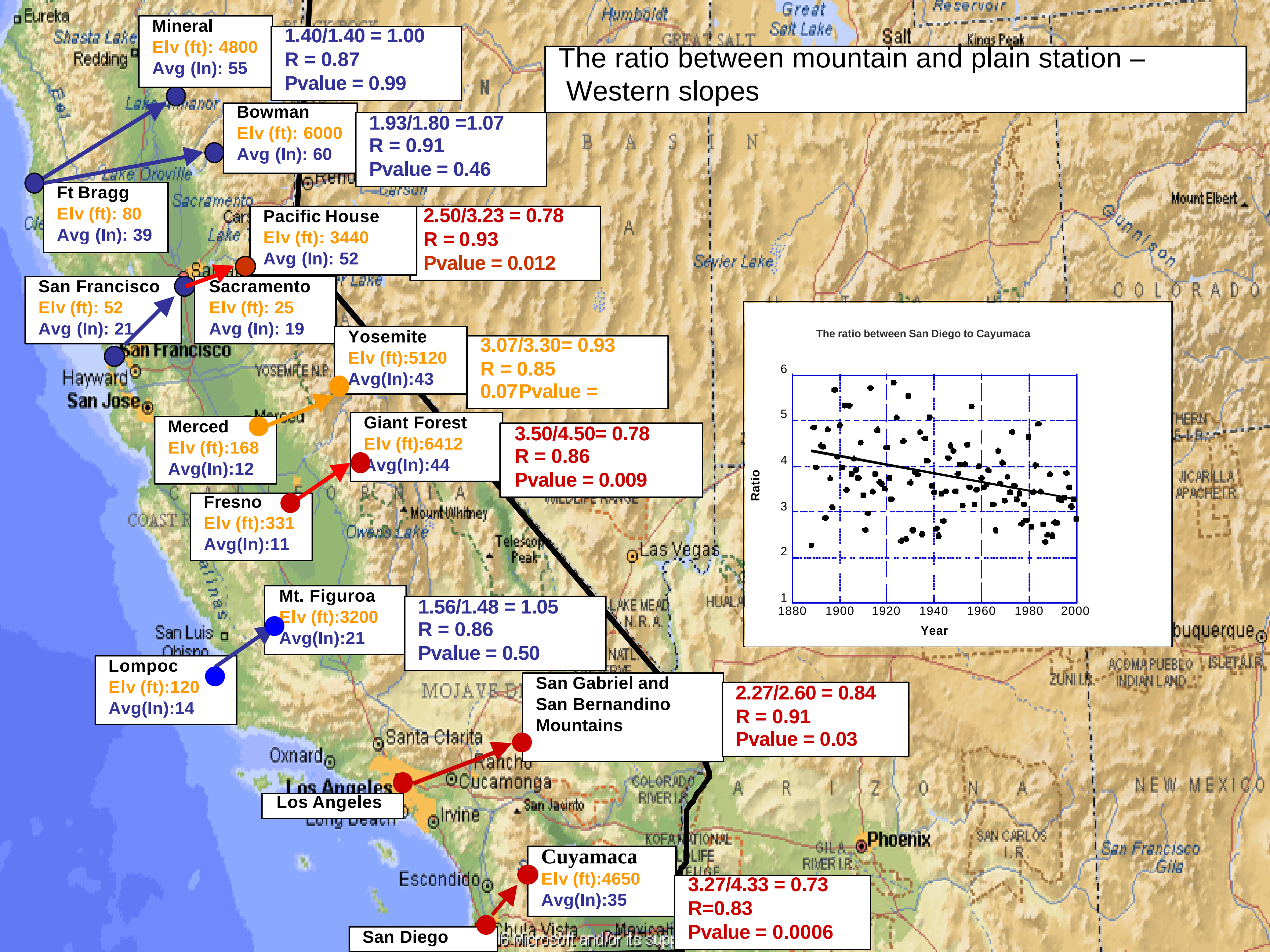
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Lompoc
Elv (ft):120
Avg(In):14
San Gabriel and
San Bernandino
Mountains
2.27/2.60 = 0.84
R = 0.91
Pvalue = 0.03
Los Angeles
Cuyamaca
Elv (ft):4650
Avg(In):35
3.27/4.33 = 0.73
R=0.83
Pvalue = 0.0006
San Diego
The ratio between San Diego to Cayumaca
Ratio
Year
1880
1900
1920
1940
1960
1980
2000
1
2
3
4
5
6

Legend

1E. Ukiah
2E. Lake Spaulding
3E. Bowman
4E. Boca
5A. San Francisco
6A. Sacramento
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8A. Cluster of snow packs in the divide line downwind to Sacramento
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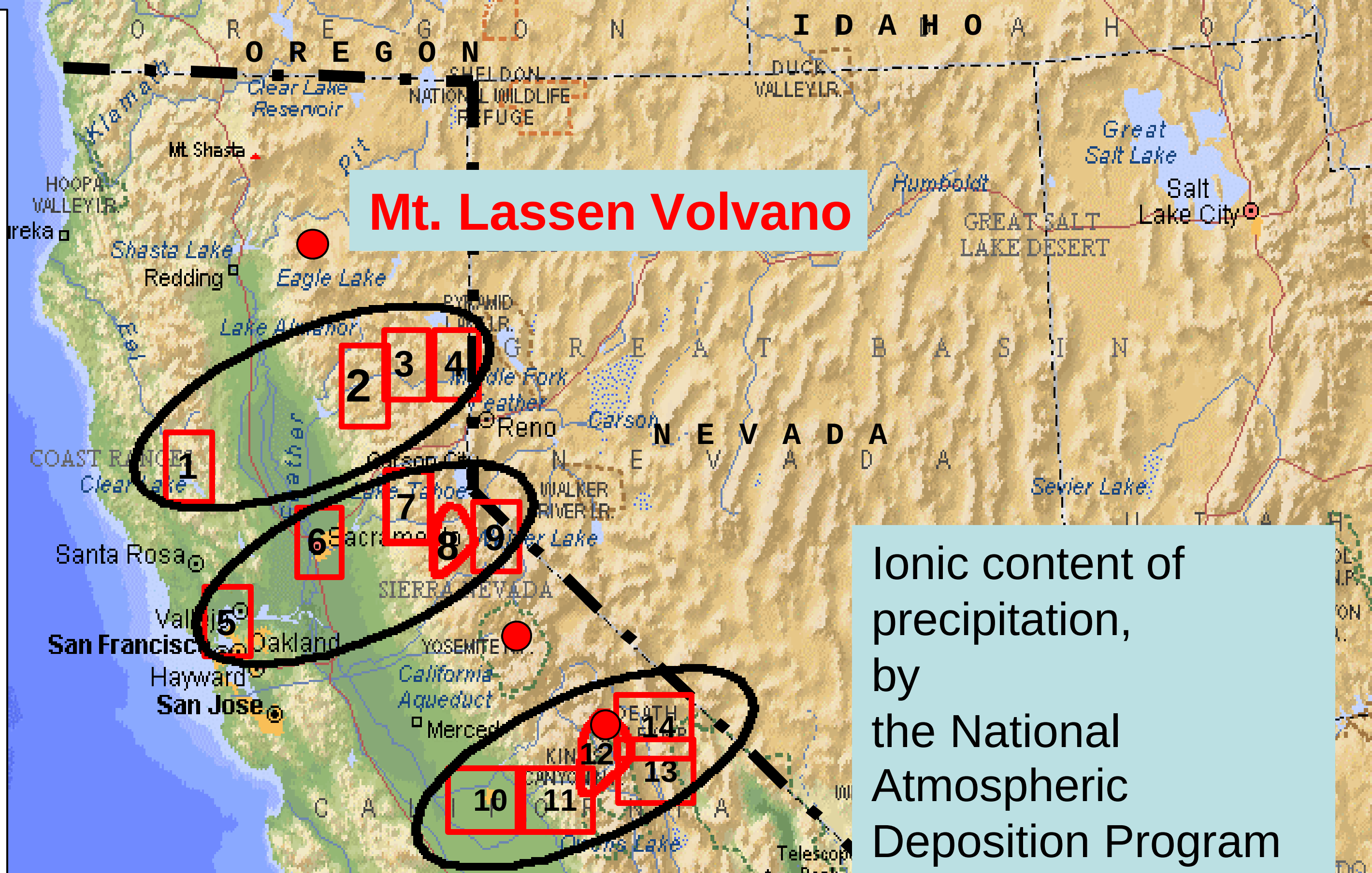
11B. Grant Grove
12B. Cluster of snow packs in the divide line downwind to Fresno
13B. Glacier
14B. Bishop Lake
15F. Lompoc
16F. Mt. Figuroa
17F. S
18F. M
19C. L
20C. (
down
21C. I
22C. I
23C. I
24. Sa
25. Cu

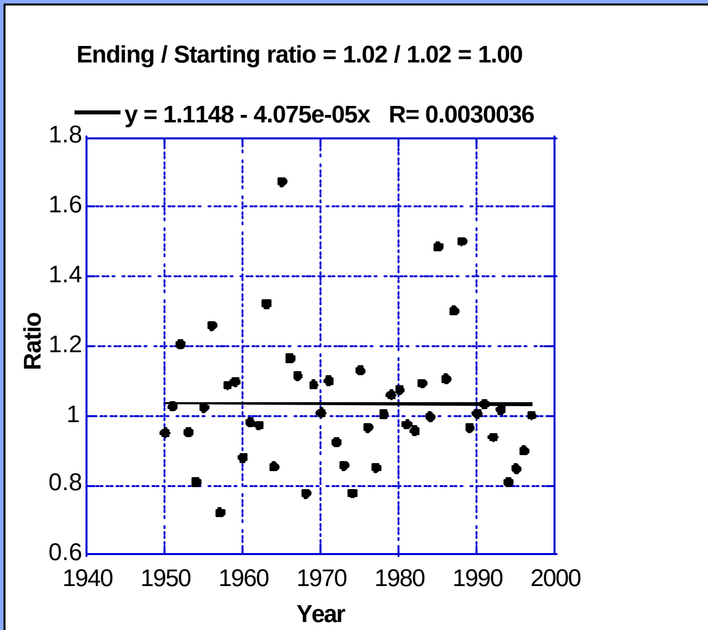


Ionic content of precipitation, by the National Atmospheric Deposition Program

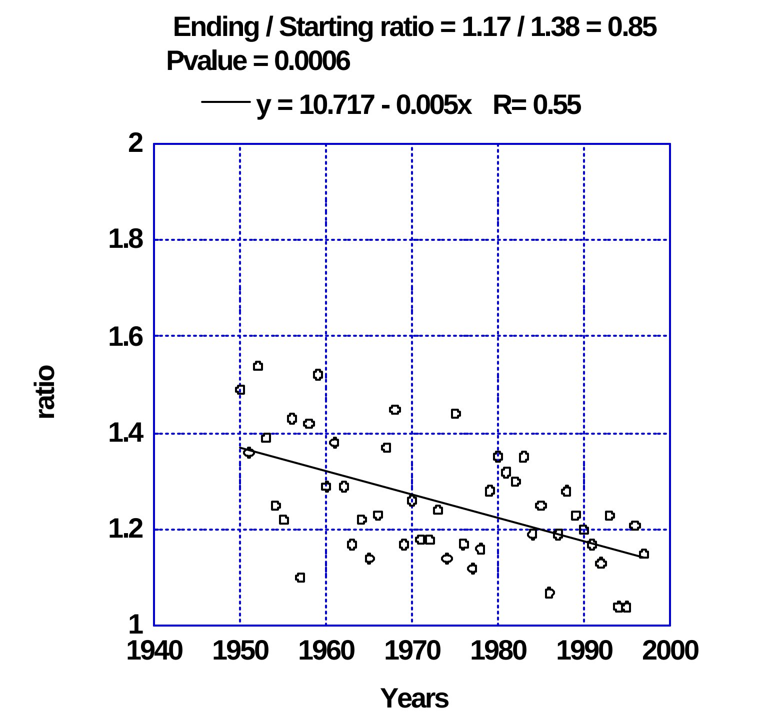
Station	Elev.(m)	Period	Mean $\mu eq\ l^{-1}$	2001-2002	Trend $\mu eq\ l\text{-}y^{-1}$	Precip. Ro change %
Sequoia/ Fresno	1902	1981-2002	41.3	35.4	+0.31	-24 (1945-2000)
Yosemite/ Sacramento	1408	1982-2002	30.7	36.5	-0.06	-22 (1945-2000)
Lassen/ Ukiah	1765	2001-2002	---	17.7	---	0 (1945-2000)

The ratio between mountain and plains stations – Western slopes

The ratio between mountain and plains stations – Western slopes

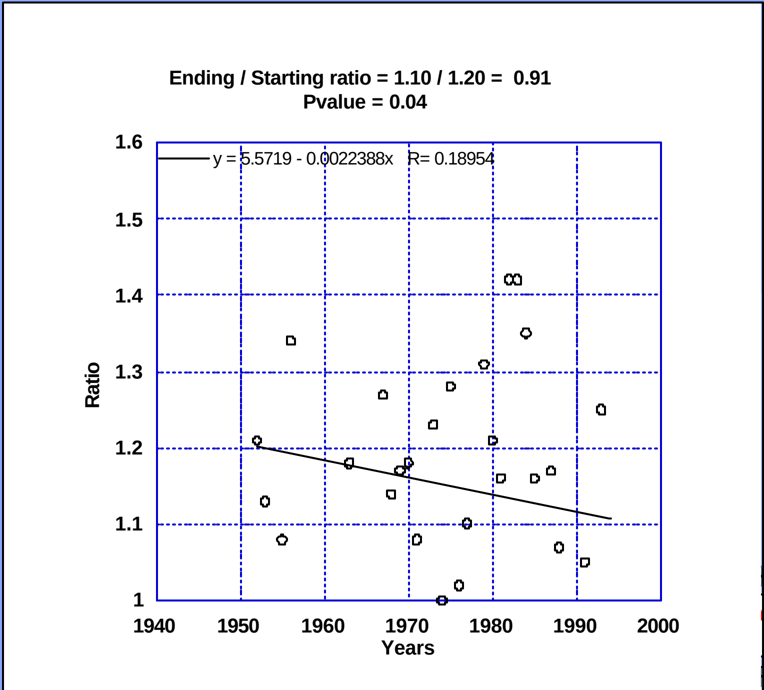


The ratio between mountain and plain station – Western slopes

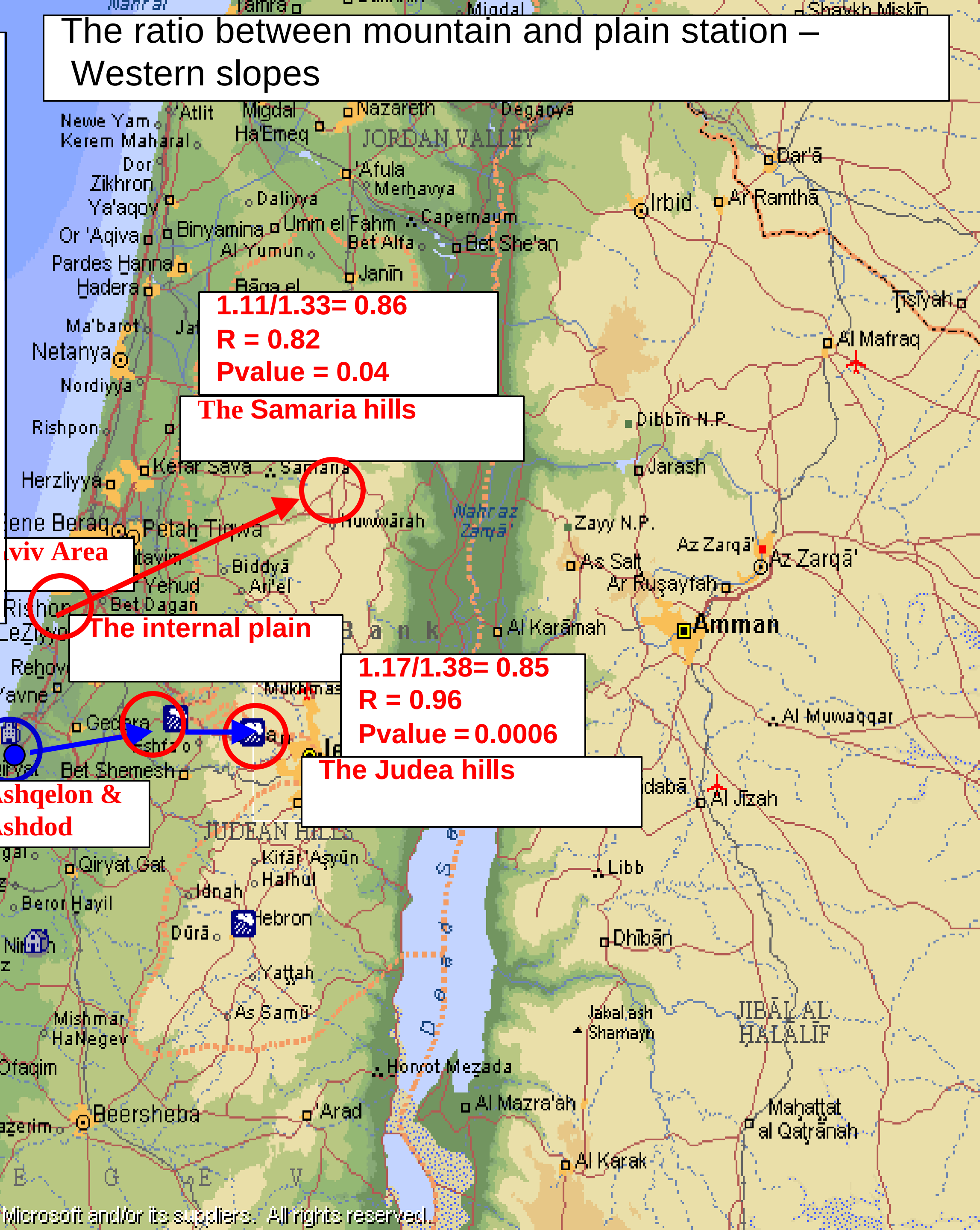


Ratio of the annual rainfall between averages of 8 mountains (Kieryat Anavim, Maale Hachamisha, Shoresh, Zova, Biet Meir, Bido, Bitonia and Ramalla) and 6 coast stations (Nacshon, Hulda, Zora, Yesodot, Mishmar David and Tel Shahar). Yearly average for the mountain stations is 648 mm and 521 mm for the coast stations. Correlation Between the mountains, coast stations is 0.96

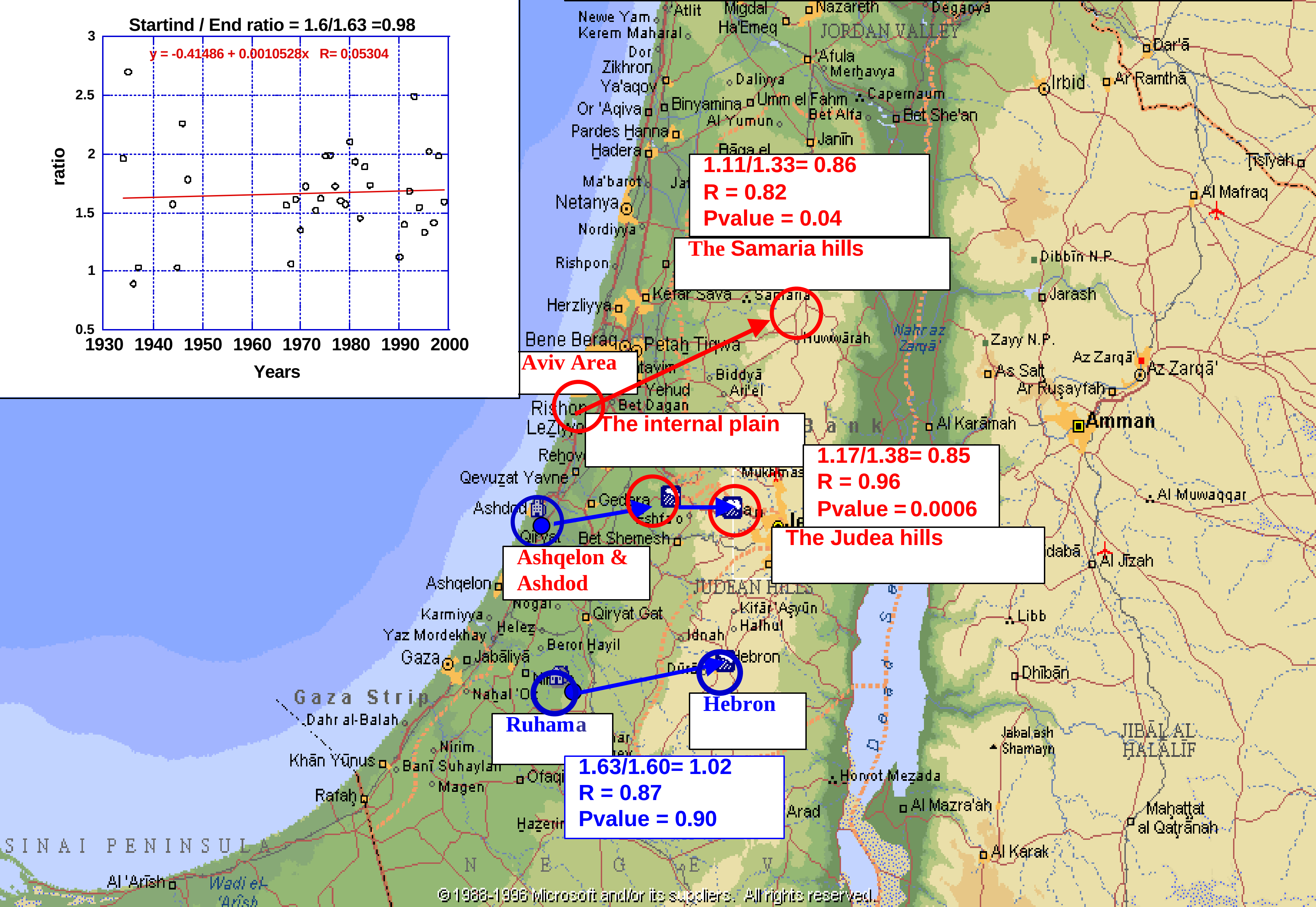
The ratio between mountain and plain station – Western slopes



Ratio of the annual rainfall between averages of 4 mountains (Nablus, Singil, Salfit,, Sabastiya,) and 5 coast stations (Tel Aviv, Bet Dagan,, Lod, Rishon-Leziyyon, Zrerifin). Yearly average for the mountain stations is 665 mm and 556 mm for the coast stations. Correlation Between the mountains, coast stations is 0.90

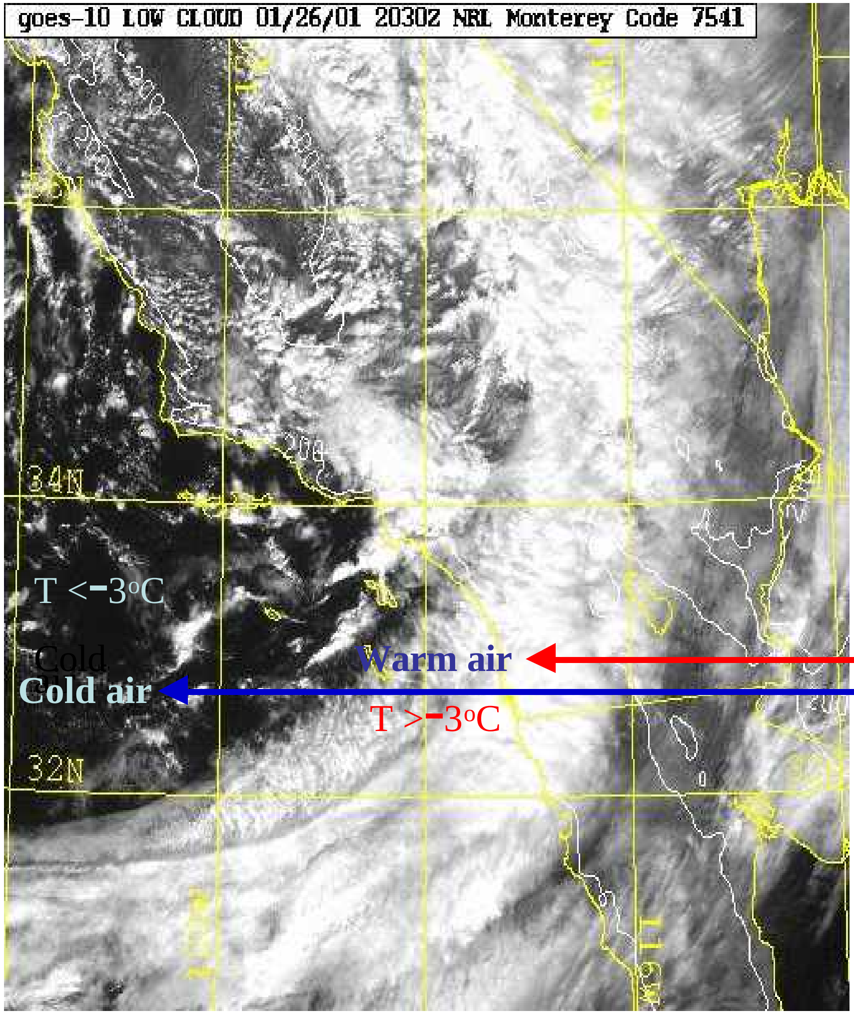


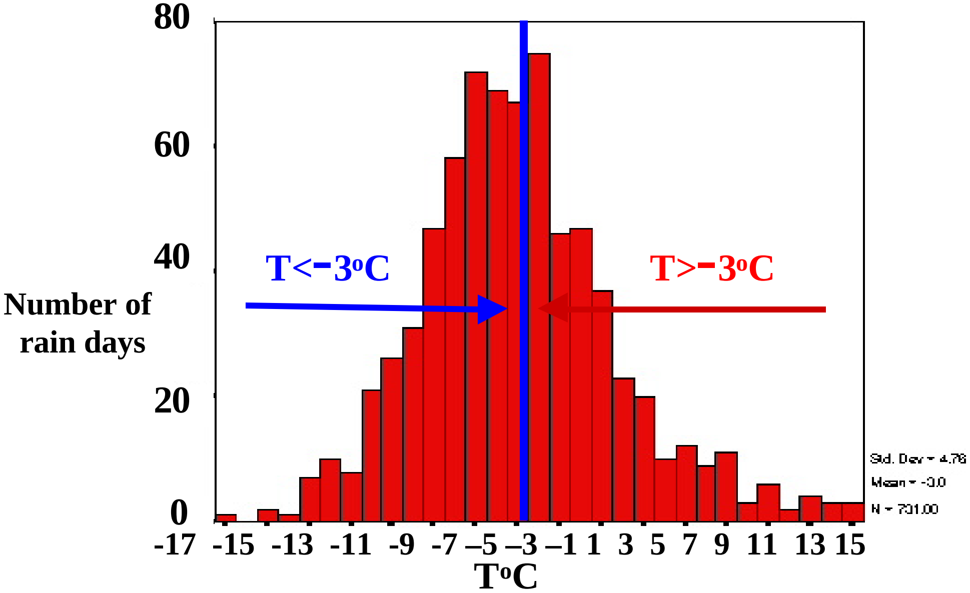
The ratio between mountain and plain station – Western slopes

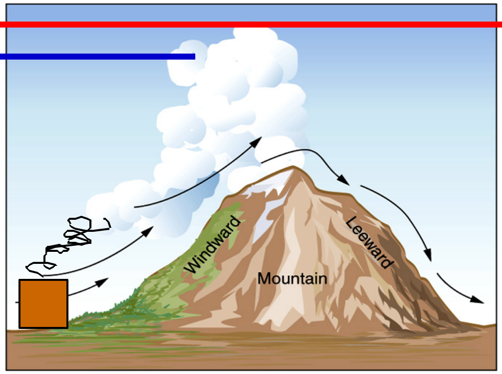


Analysis of the orographic factor trends according to the synoptic conditions:

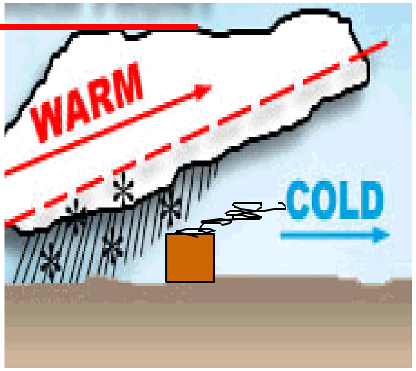
- 3ºC : Expected Clouds Temperatures at 700 mb on rainy days - Los Angeles and San Diego areas



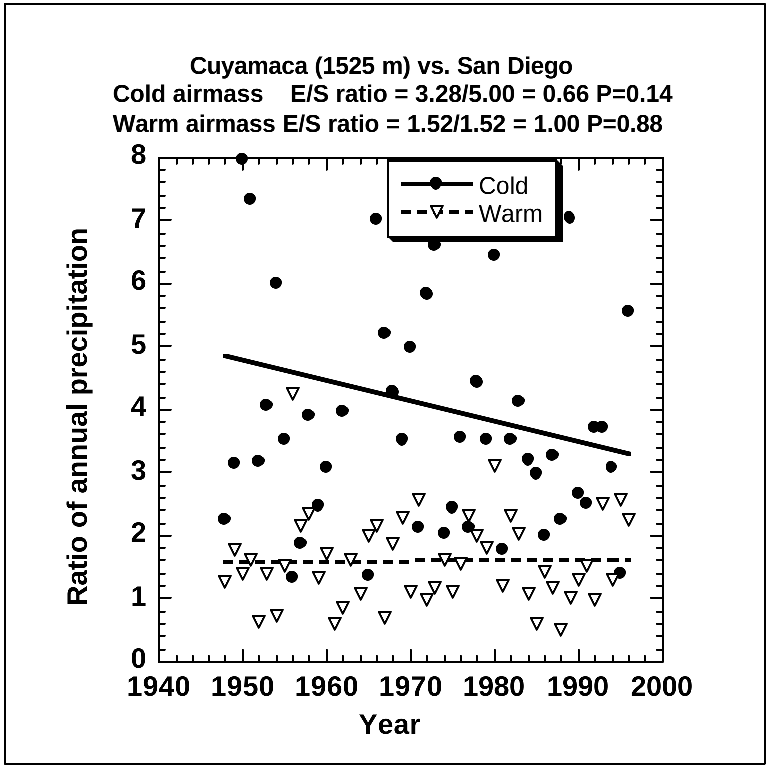


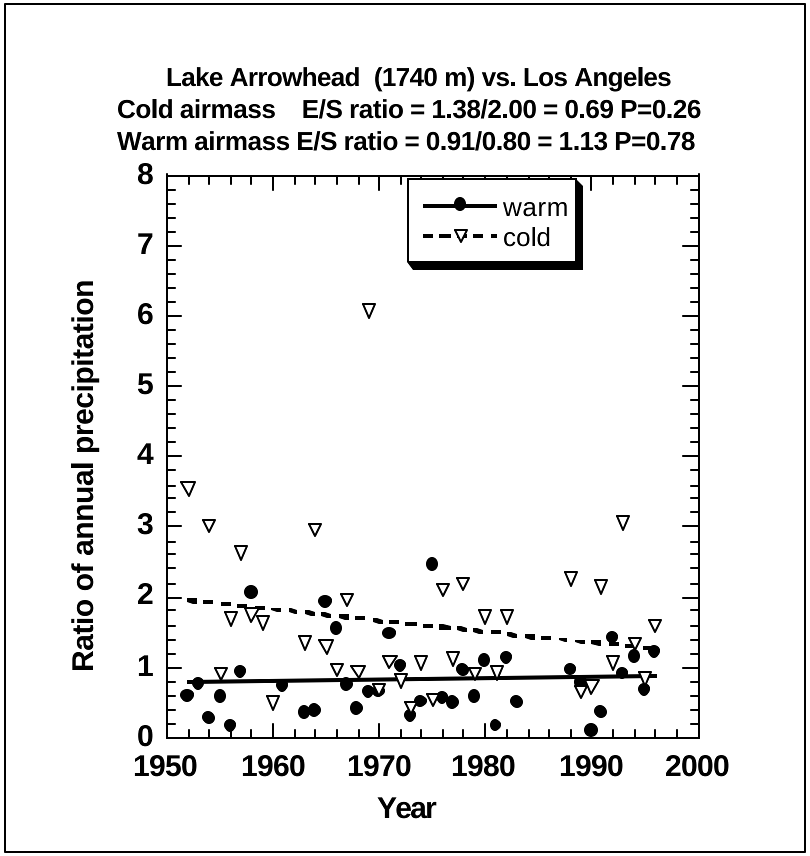


(c) Orographic (barrier)



The annual ratios of precipitation (Ro) between Cuyamaca and San Diego for clouds occurring when T>-3ºC at 700 hpa (mainly frontal and warm air mass) and when T ≤ -3ºC (mainly cyclonic post frontal clouds).





The radiosonde model

In order to separate and identify the human potential causes from natural processes, such as changes in the atmospheric circulation, a model that predicts the natural rain in the mountain was calculated :

$$RMM = (RCM*X1) + (WCOMP*W*X2) + Const$$

RMM is the predicted precipitation In the mountains

RCM is the gauged precipitation at the coast

WCOMP is the wind speed component toward the mountain (850 mb)

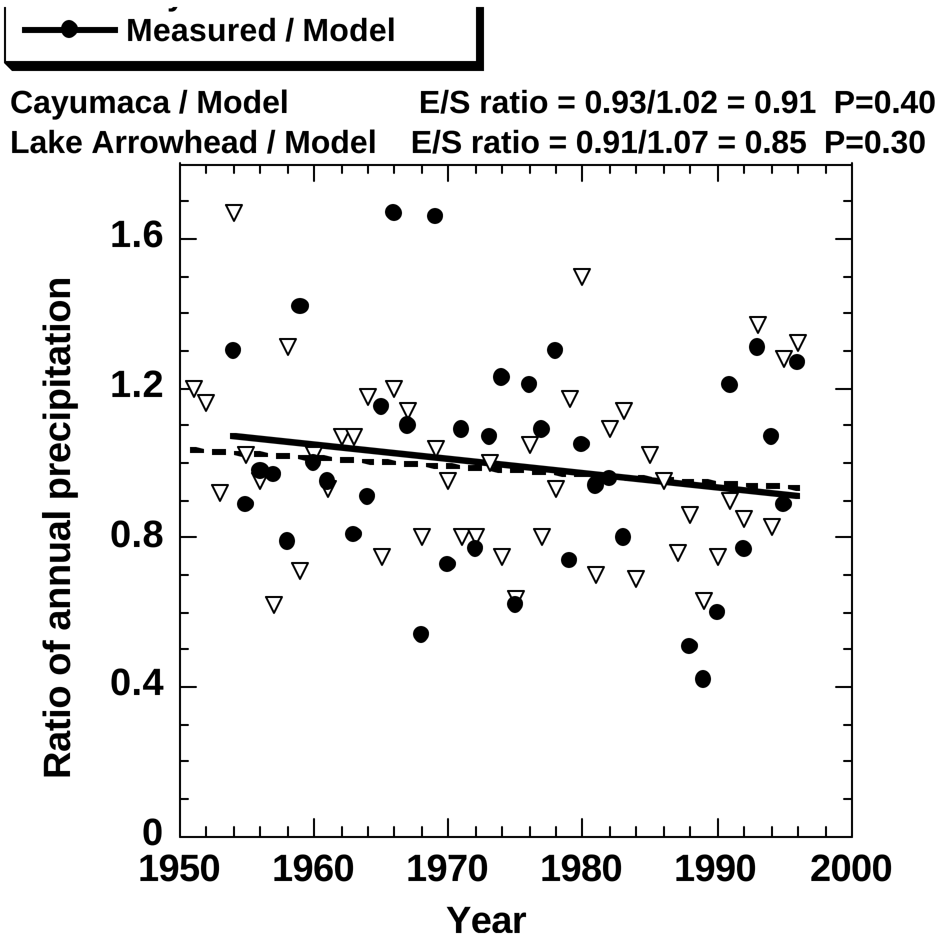
W is the mixing ratio (850 mb)

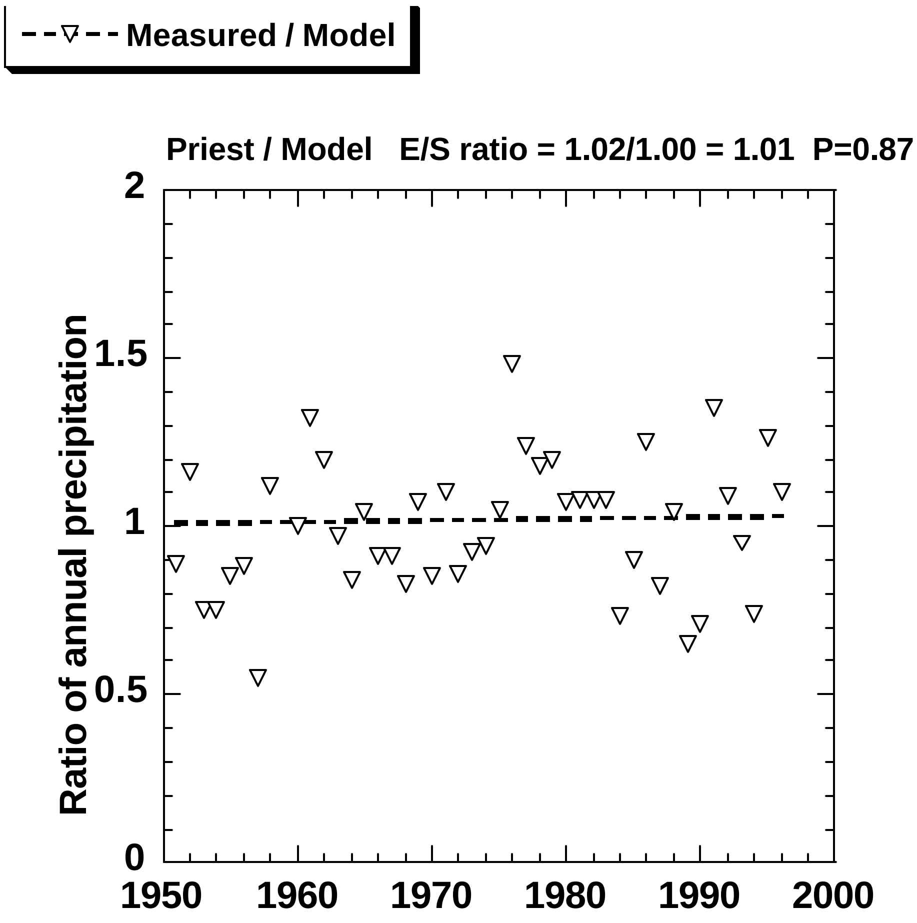
Const is the multiple regression constant

The radiosonde model results – California :

The ratio between measured daily precipitation to the model-predicted daily precipitations (R = 0.80 and 0.75) in polluted areas (San Diego and Los Angeles areas)

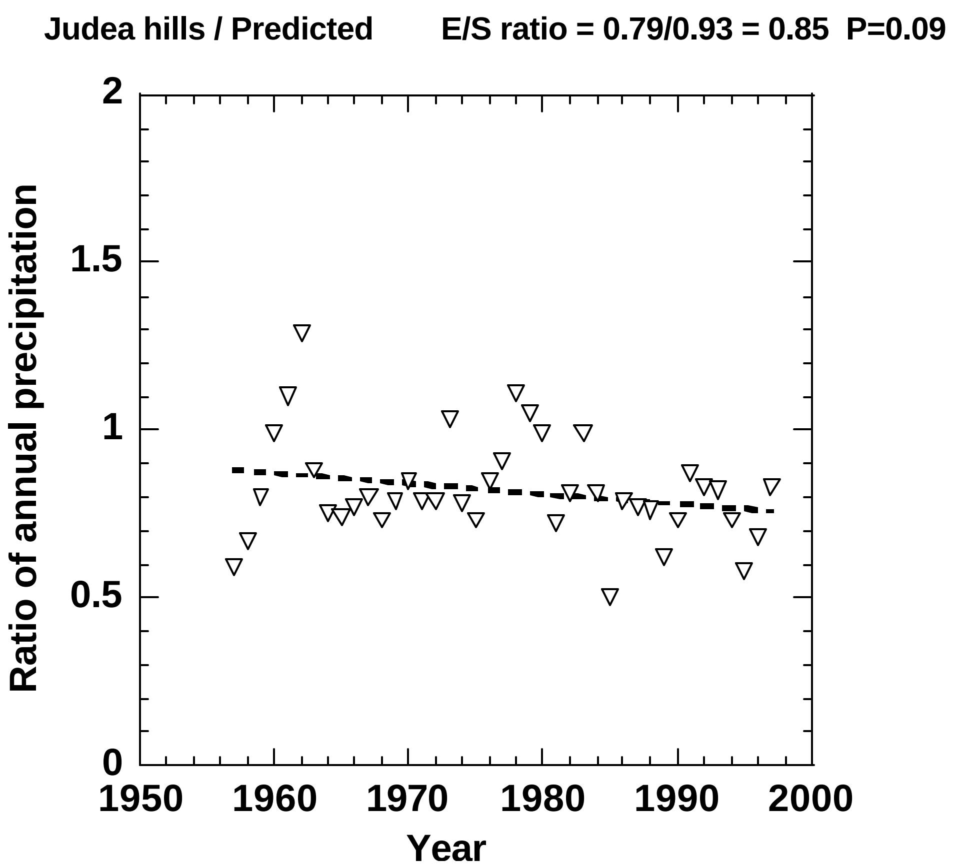
The ratio between measured daily precipitation to the model predicted daily precipitation (R=0.86) in a "clean" area (Monterey county)



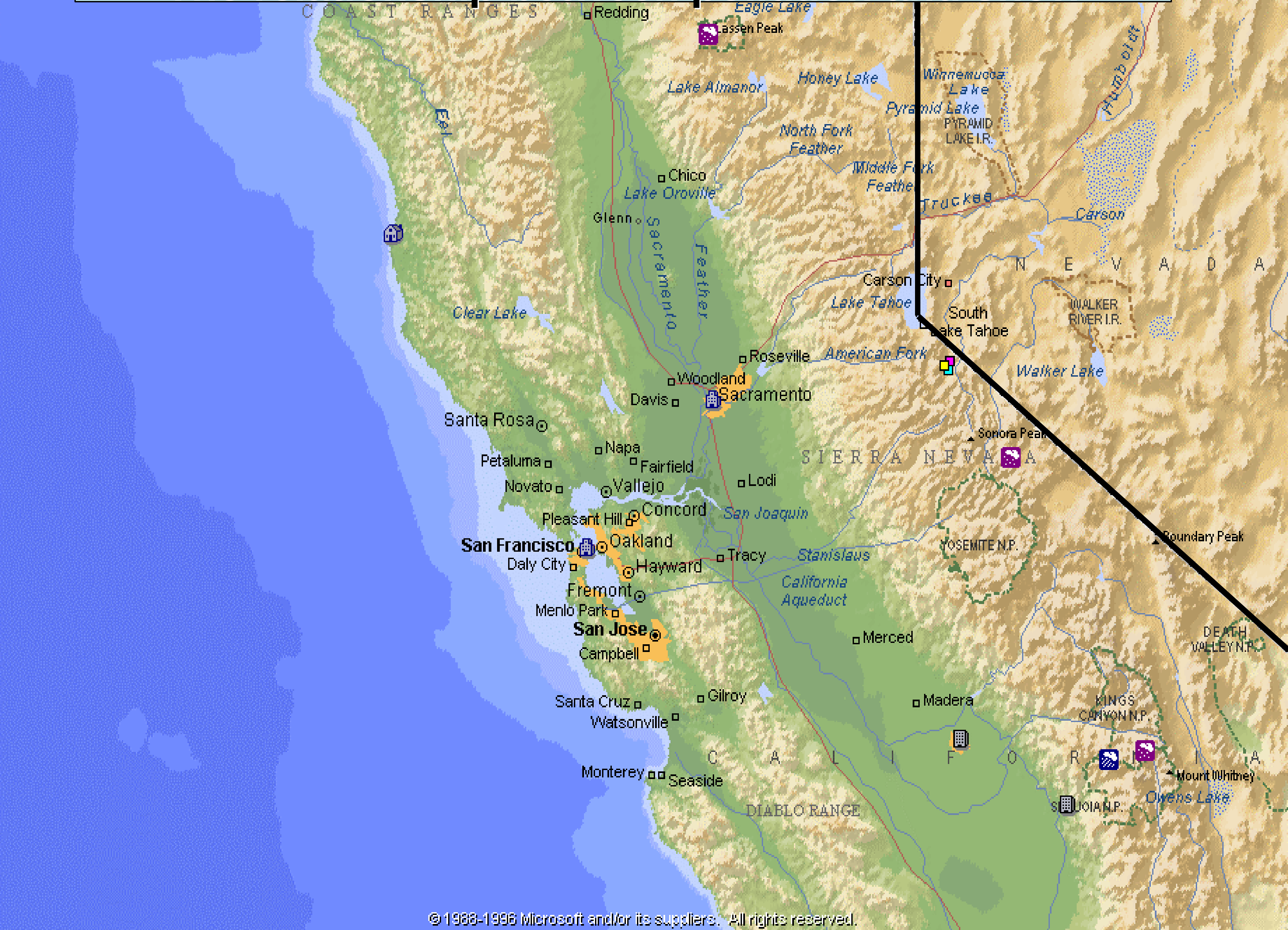


The radiosonde model results – Israel :

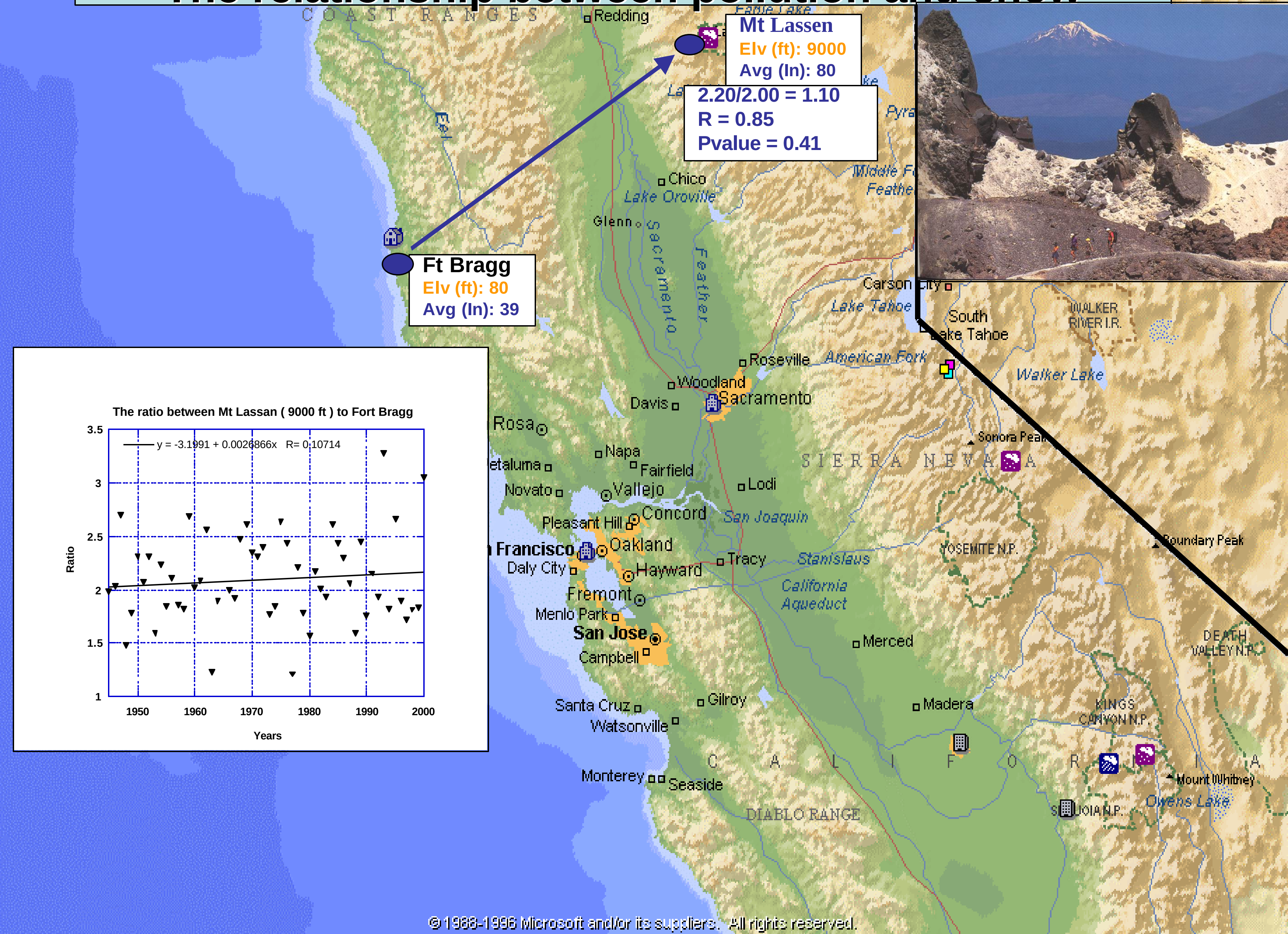
The ratio between measured daily precipitation in the **Judea** hills to the model predicted daily precipitation (R = 0.87) in a polluted area



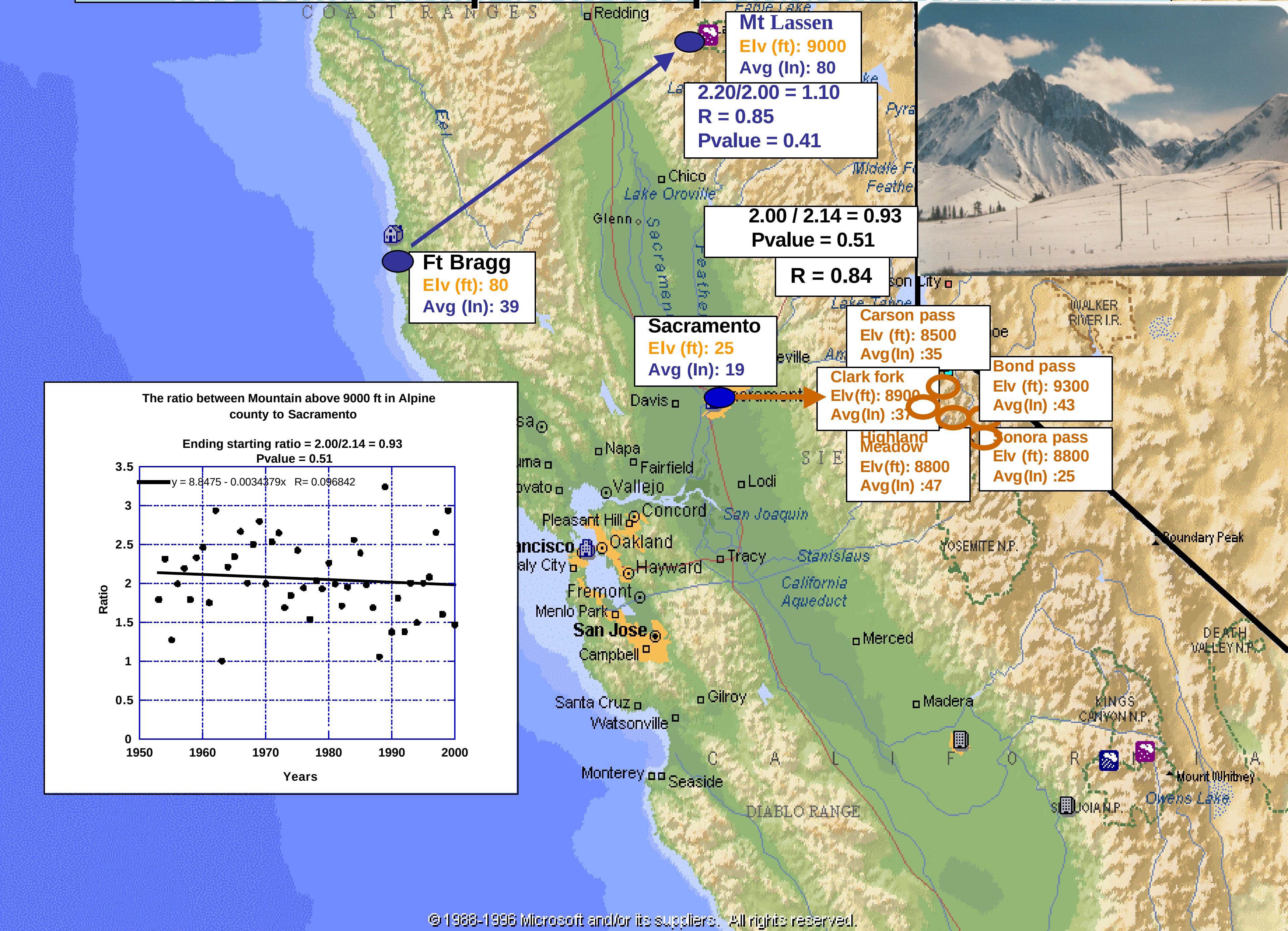
The relationship between pollution and snow



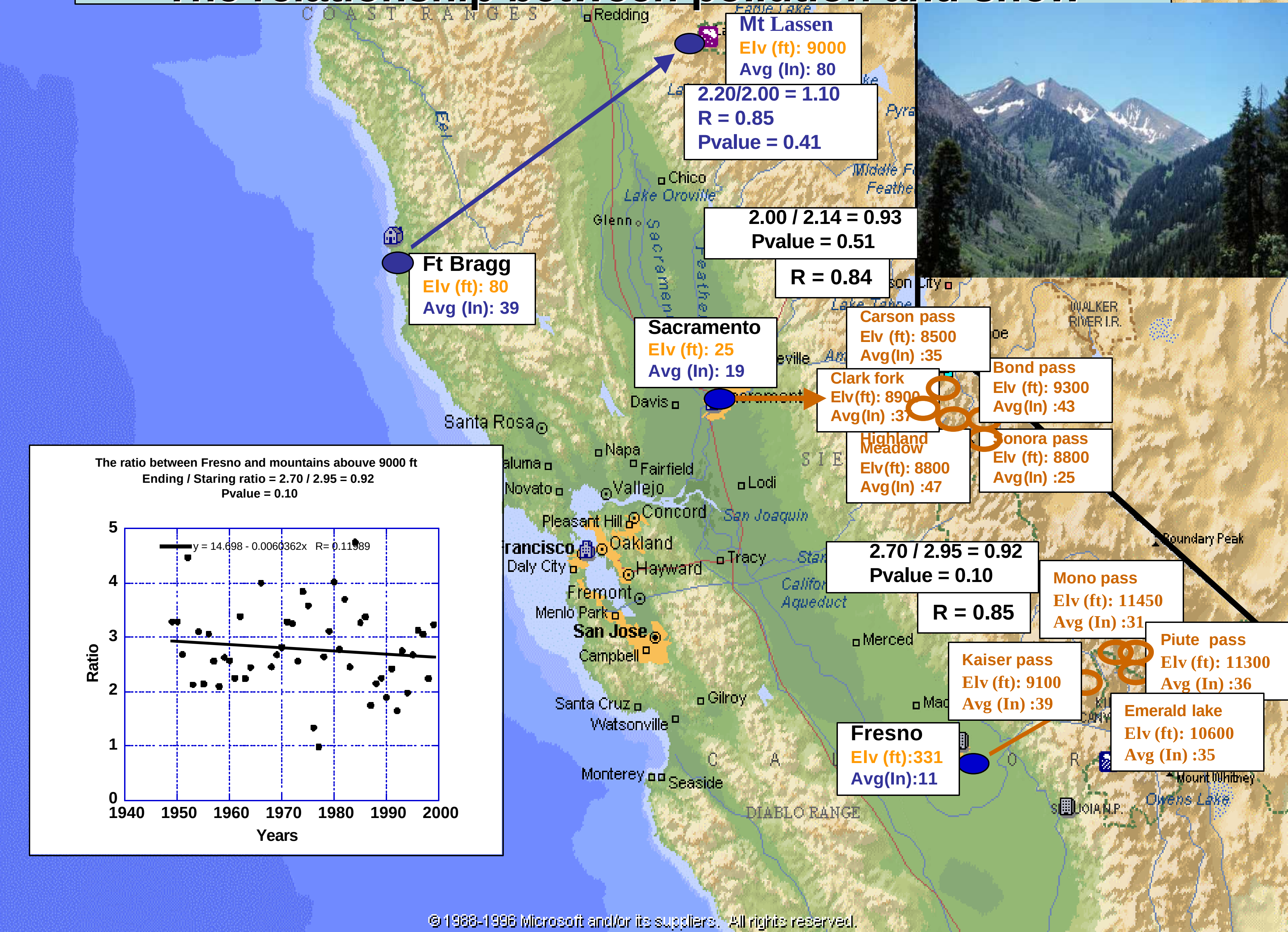
The relationship between pollution and snow



The relationship between pollution and snow

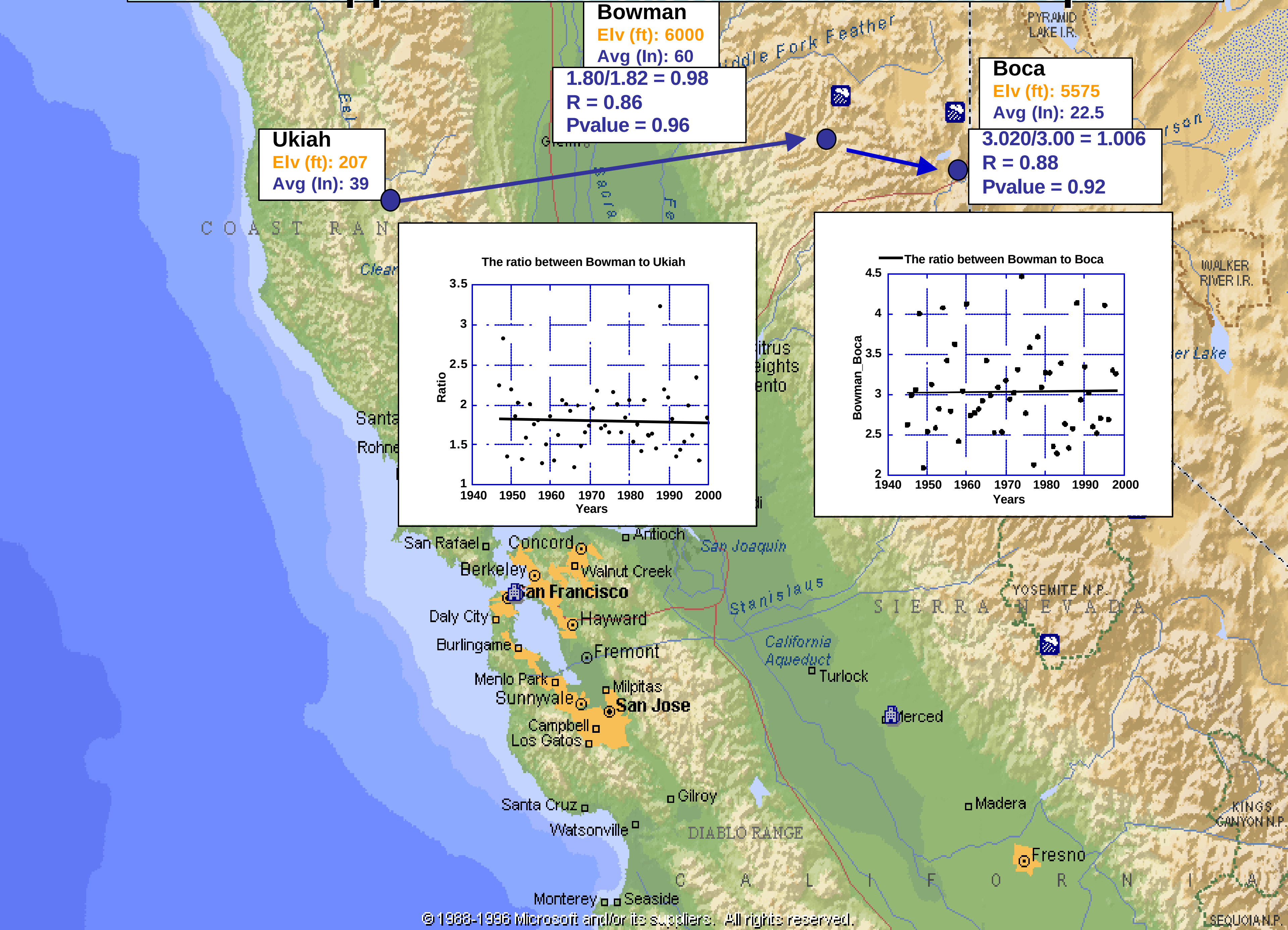


The relationship between pollution and snow

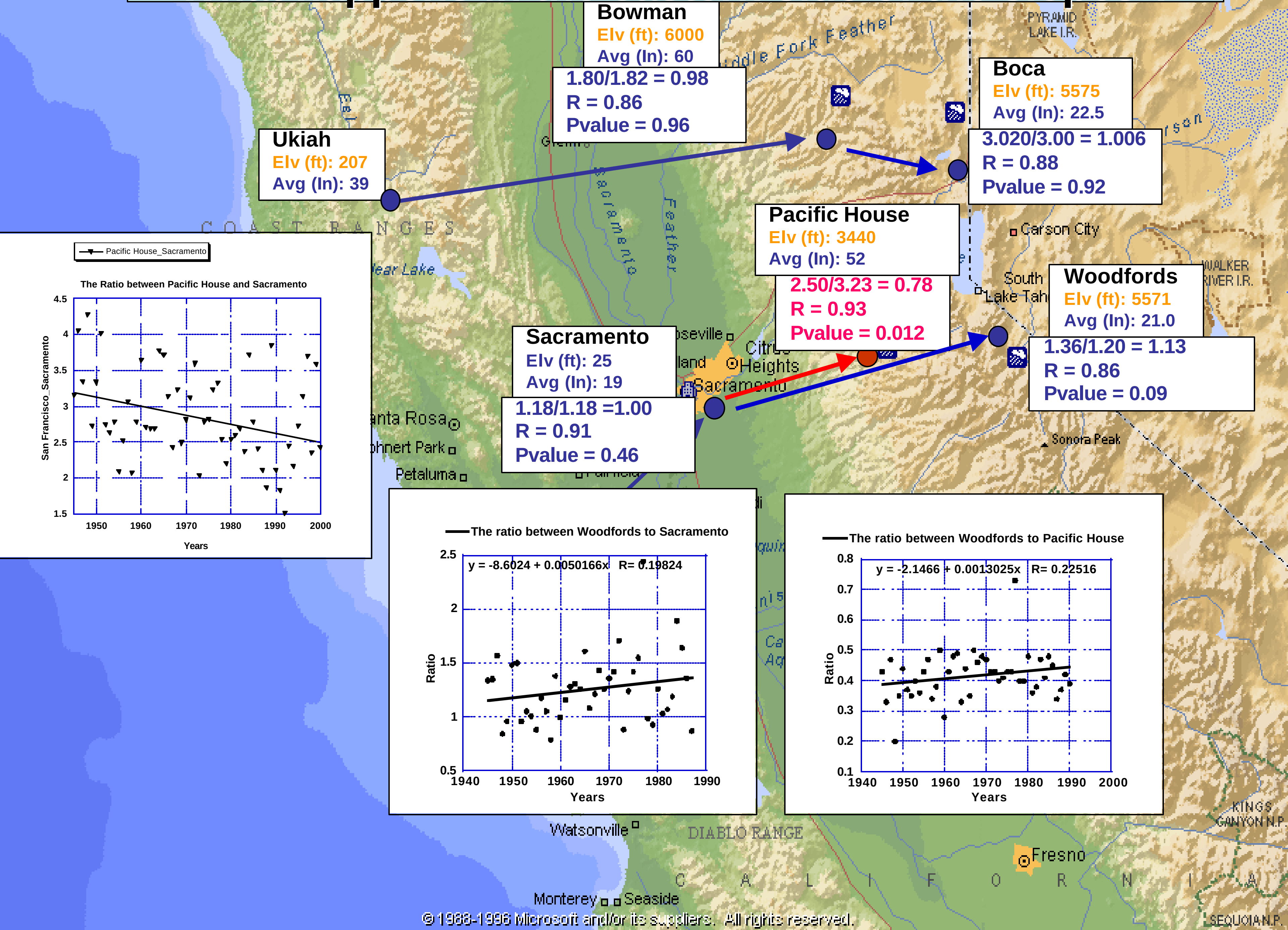


What happens on the eastern side of the slopes ?

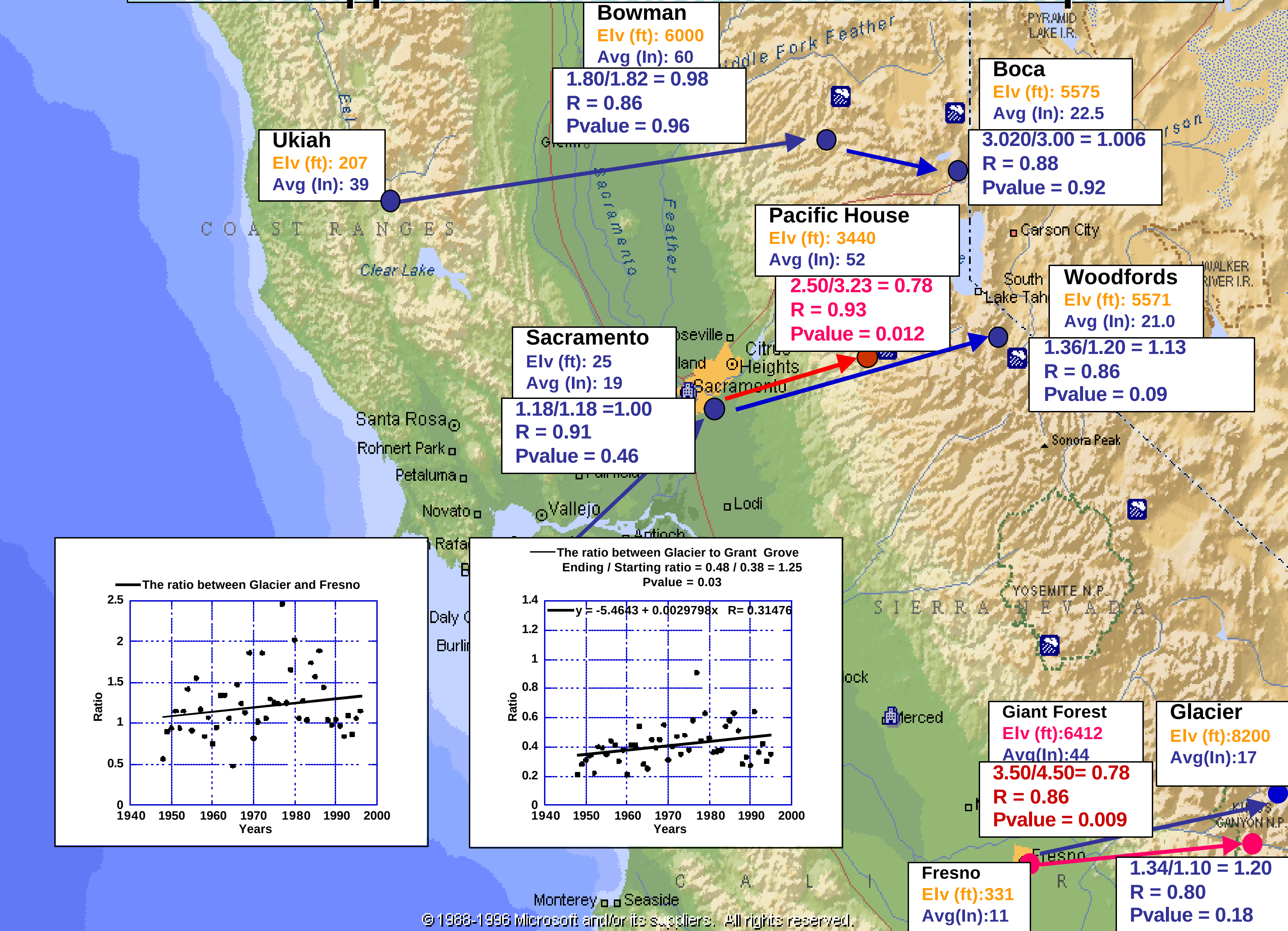
What happens in the eastern side of the slopes ?



What happens in the eastern side of the slopes ?

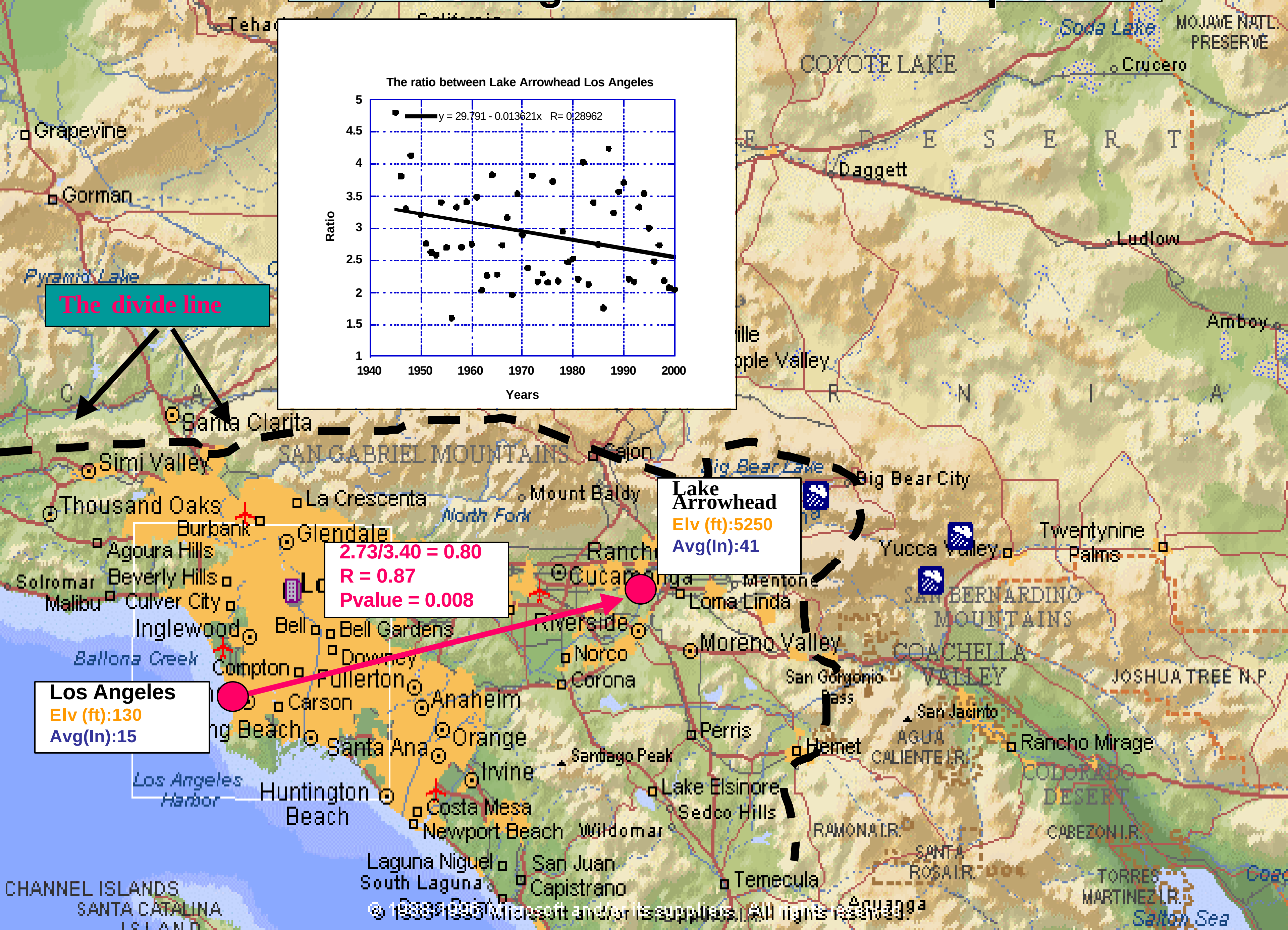


What happens in the eastern side of the slopes ?

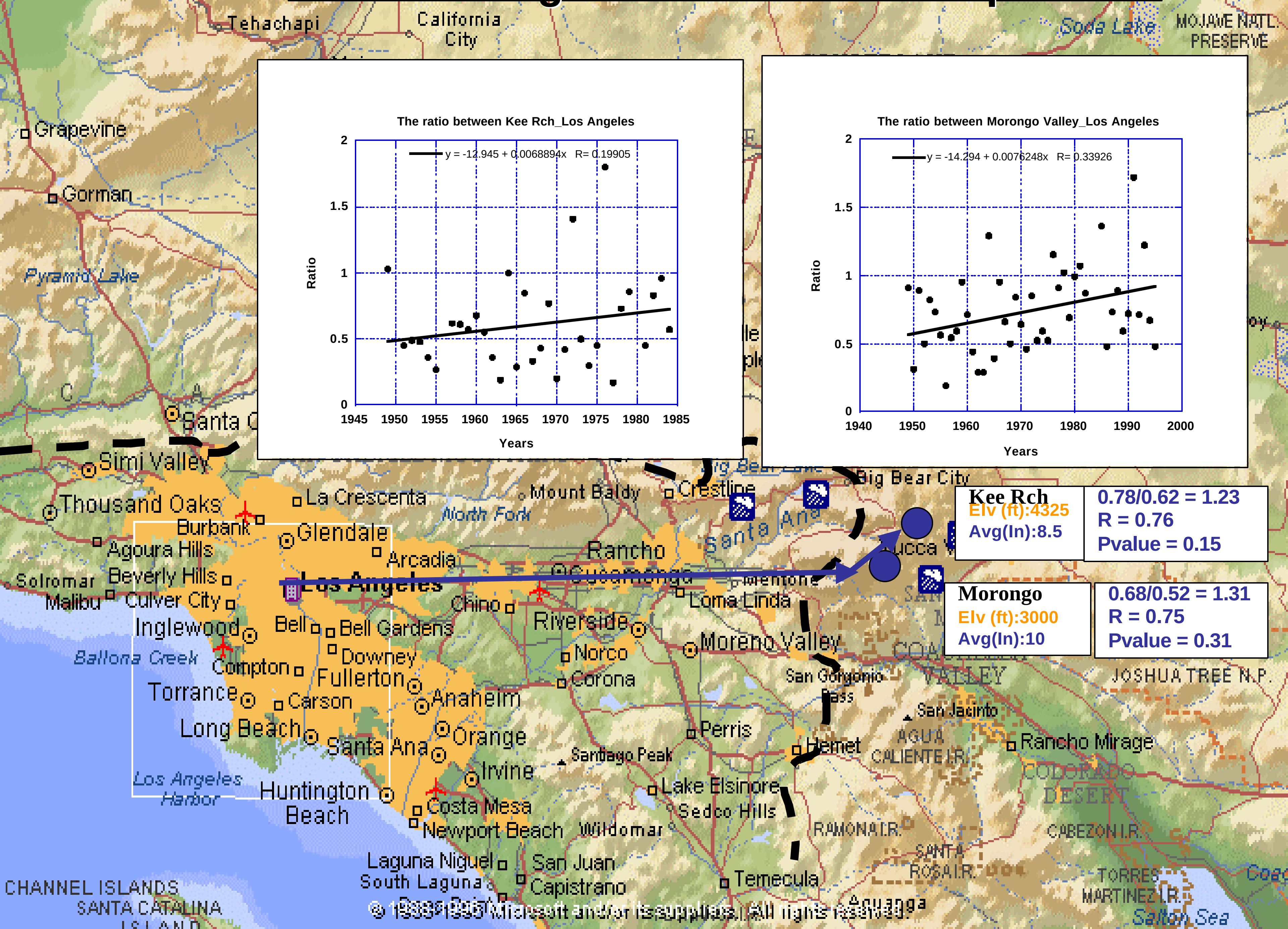


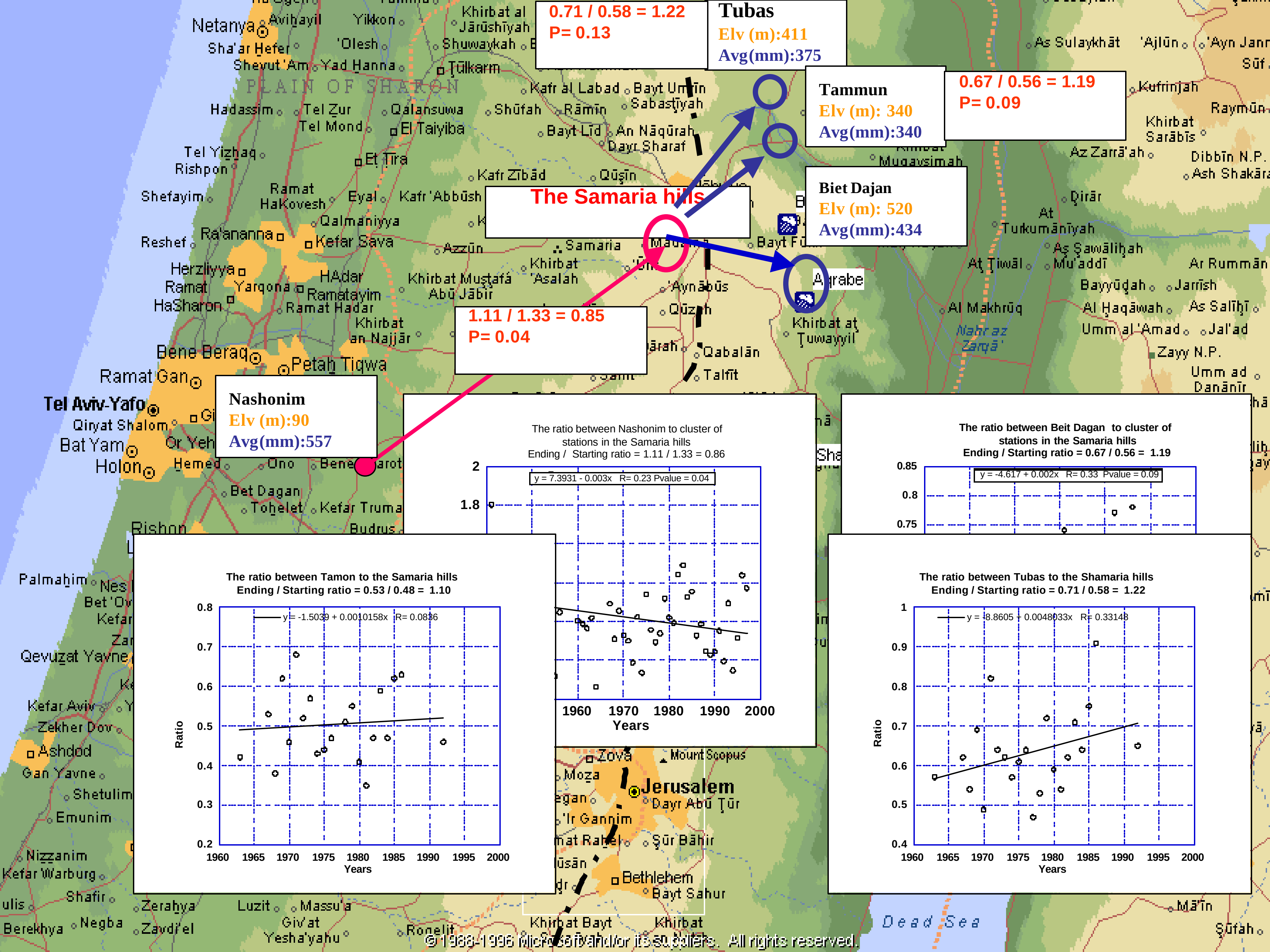
Los Angeles area eastern slopes

Los Angeles area eastern slopes



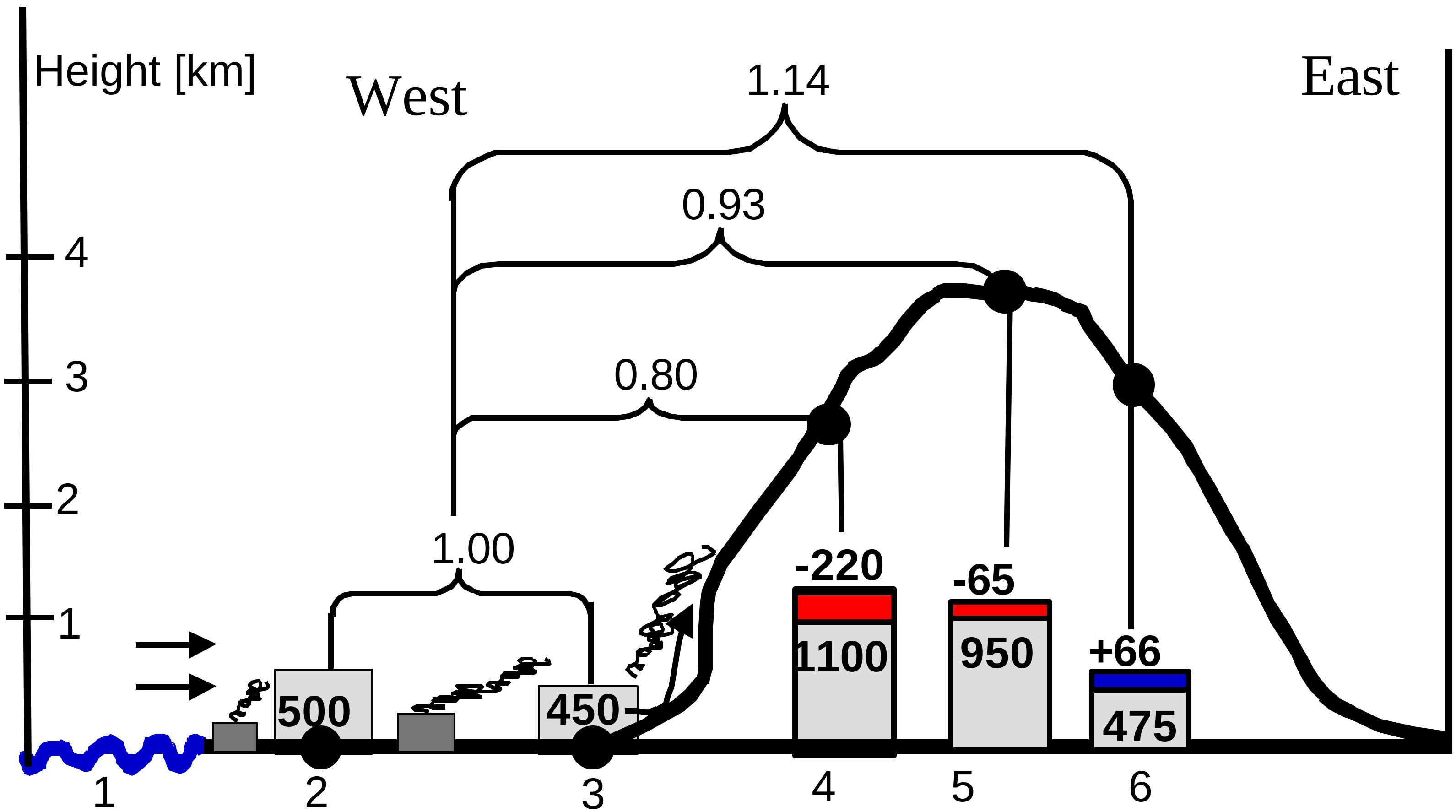
Los Angeles area eastern slopes





0.71 / 0.58 = 1.22
P= 0.13
Tubas
Elv (m):411
Avg(mm):375
Tammun
Elv (m): 340
Avg(mm):340
0.67 / 0.56 = 1.19
P= 0.09
Biet Dajan
Elv (m): 520
Avg(mm):434
The Samaria hills
1.11 / 1.33 = 0.85
P= 0.04
Nashonim
Elv (m):90
Avg(mm):557
The ratio between Nashonim to cluster of stations in the Samaria hills
Ending / Starting ratio = 1.11 / 1.33 = 0.86
y = 7.3931 - 0.003x R= 0.23 Pvalue = 0.04
Years
The ratio between Beit Dagan to cluster of stations in the Samaria hills
Ending / Starting ratio = 0.67 / 0.56 = 1.19
y = -4.617 + 0.002x R= 0.33 Pvalue = 0.09
The ratio between Tamon to the Samaria hills
Ending / Starting ratio = 0.53 / 0.48 = 1.10
y = -1.5039 + 0.0010158x R= 0.0836
Ratio
Years
The ratio between Tubas to the Shamaria hills
Ending / Starting ratio = 0.71 / 0.58 = 1.22
y = -8.8605 + 0.0048033x R= 0.33148
Ratio
Years
Tel Aviv-Yafo
Jerusalem
Dead Sea
PLAIN OF SHARON

Topographic cross section showing the effects of urban air pollution
on precipitation as the clouds move from west to east across the Sierra Nevada




E/S=1.10, P=0.50
E/S=1.10, P=0.13
Mt. Figuroa
Mt. Pine
Lompoc
Santa Barbara
Distance in Km
0
90
Bakersfield
Greenacres
Kern City
McKittrick
Tupman
Caliente
Lamont
Arvin
Buena Vista Lake Bed
Ford City
Taft
Maricopa
San Luis Obispo
Salinas
Oceano
Nipomo
Twitchell Reservoir
Santa Maria
TEHACHAPI MOUNTAINS
Grapevine
Lebec
California Aqueduct
Pyramid Lake
Los Alamos
Vandenberg Village
Mission Hills
Lompoc
LOMPOC VALLEY
SANTA YNEZ I.R.
Cachuma Lake
Las Cruces
Tajiguas
Point Conception
SANTA YNEZ MOUNTAINS
Goleta
Isla Vista
Carpinteria
Punta
Sea Cliff
Ojai
Fillmore
Santa Paula
Sulpher Springs
Santa Clara
Santa Clarita
Ventura
Montalvo
Saticoy
Moorpark
Simi Valley
Chatsworth
Chatsworth Reservoir
Northridge
SAN FERNANDO VALLEY
Encino
El Rio
Camarillo
Thousand Oaks
Oxnard
Port Hueneme
Westlake Village
Agoura Hills
SANTA MONICA MOUNTAINS N.R.A.
Point Mugu
Malibu
Santa Monica
Santa Barbara Channel
SAN MIGUEL ISLAND
SANTA CRUZ ISLAND
CHANNEL ISLANDS N.P.

Conclusions:

- All time series from metropolitan areas in California show a decrease in the ratio between the mountain and coastal stations along the years (mostly between 1950 to 1980) . Similar trends were found also in Israel

- In the control areas, no change at all in the orographic enhancement factor was detected, both in California and in Israel

- The decrease was found only in cold air masses with clouds ingesting the air from the polluted boundary layer.

- Based on the sounding analyses, no evidence was found that can explain natural trends in the orographic enhancement factor in California and Israel

- **The likely explanation for the 15%-25% decreasing orographic rainfall is the air pollution**

Research Recommendations

Satellite Microphysical Survey

Numerical Modeling with Explicit Microphysics and Varying Aerosol Inputs

Measurements of Aerosol Burden and Transport in California

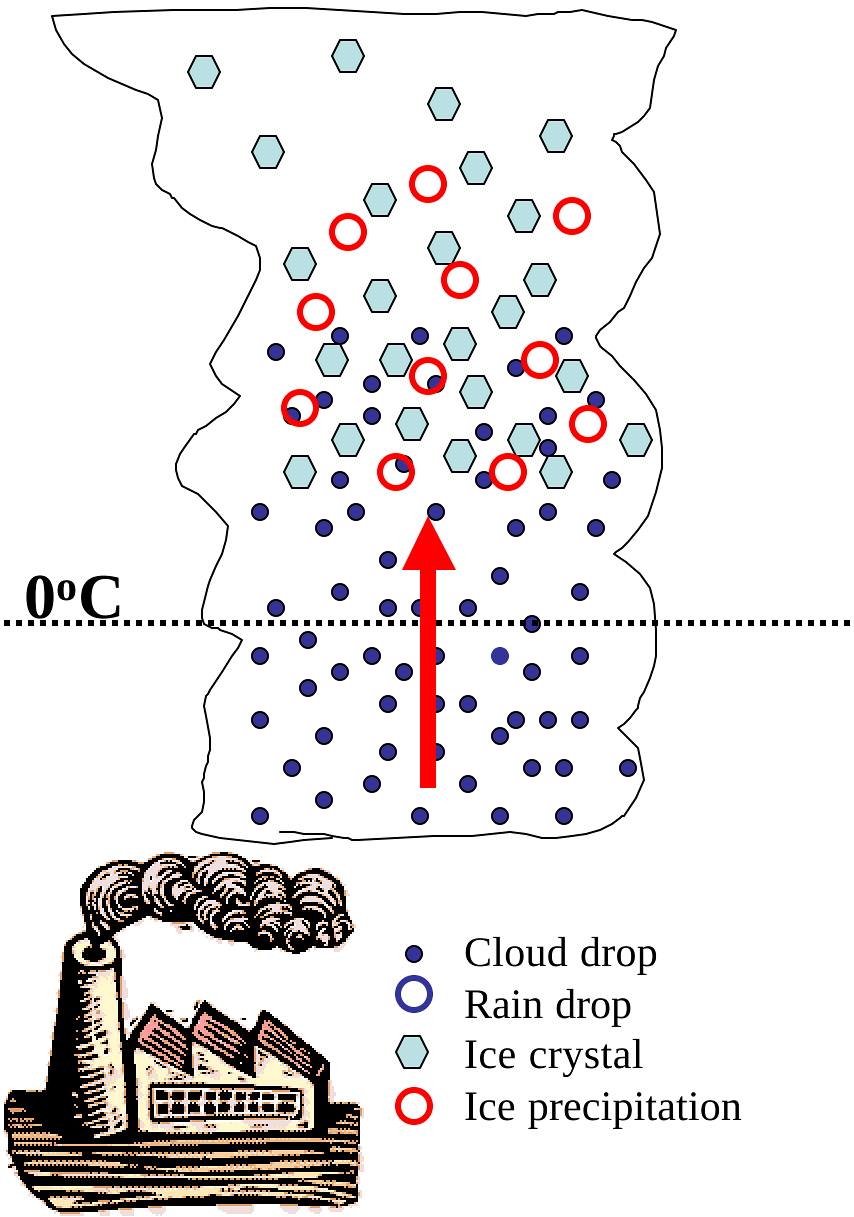
Analyses to Separate Out Effects of Glaciogenic Seeding from Effects of Pollution

Additional Measurements of the Effects of Anthropogenic Aerosols on Snow Growth and Snowfall Rate

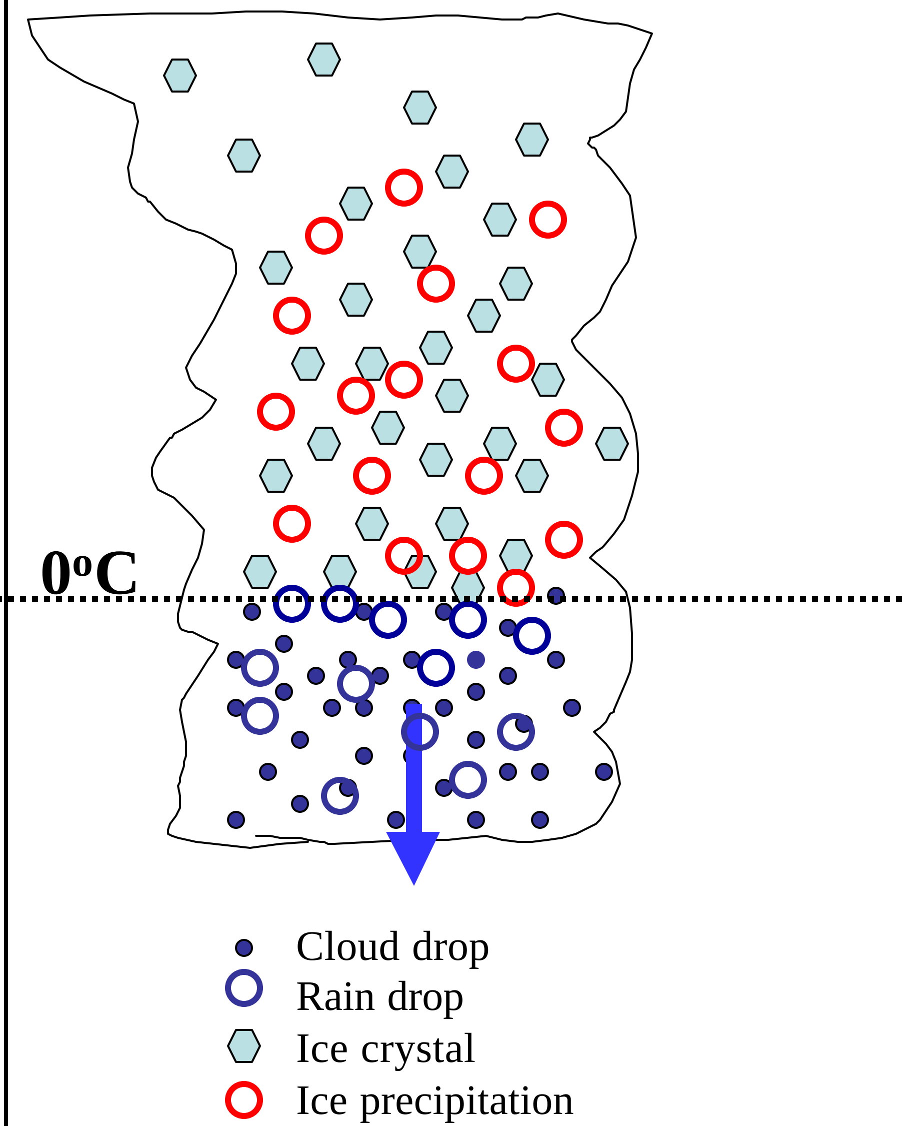
Develop Relationships Relating Precipitation to Runoff

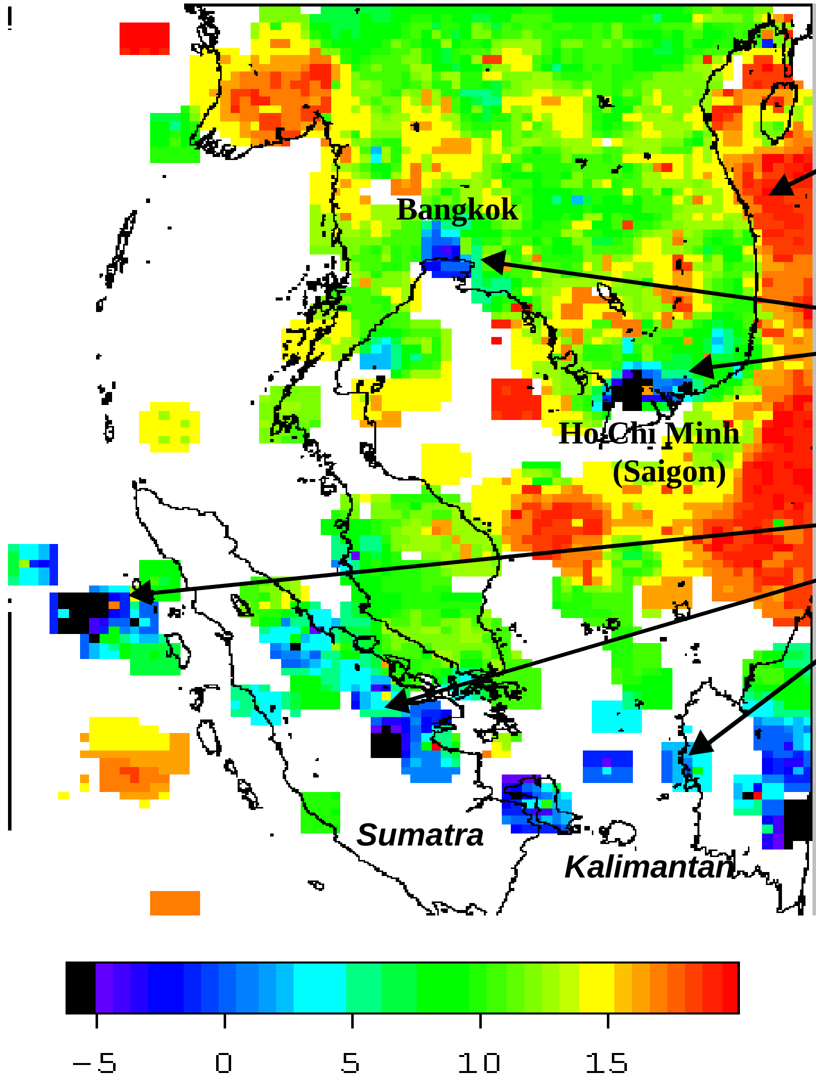
Dr. Woodley's formal presentation ended at this point. The following slides have been left in this presentation for those who are interested in more information on this subject.

Continental: Polluted, Suppressed rain, Strong updraft



Maritime: Clean, Fast rain, Suppressed updraft





*The effect of aerosols on precipitation in clouds was calculated from the data of the image above. The **warm colors** represent efficient precipitation processes, while the **cold colors** represent suppressed precipitation, due to the pollution. The scale is the maximal cloud top temperature [^{0}C] required for onset of precipitation.*

(1) *Maritime and Rural aerosols*

Clouds from ***clean maritime*** air **develop precipitation efficiently**. After interacting with ***rural aerosols***, the clouds are **less efficient in developing precipitation.**

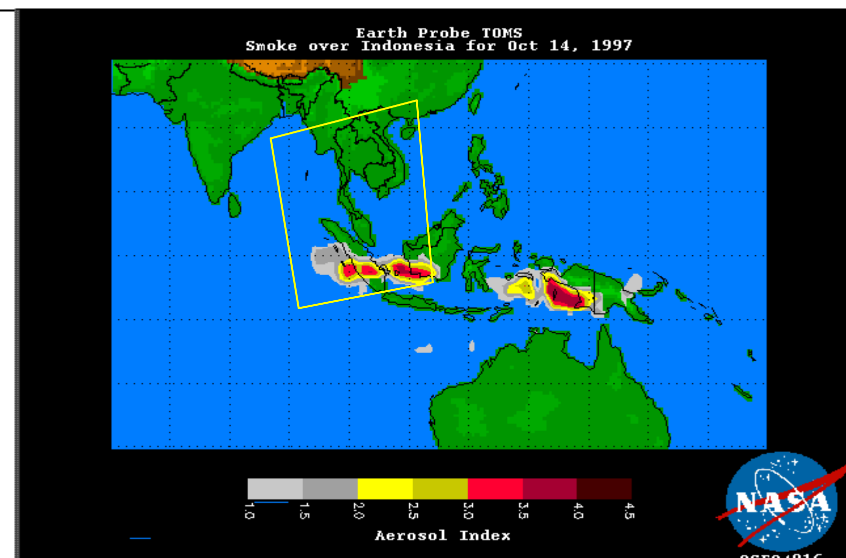
(2) *Urban air pollution*

The **blue color** indicates detrimental effect of ***urban air pollution*** on the precipitation in the clouds.

(3) *Smoke from forest fires*

Another case of detrimental effect of the interaction of Clouds with biomass burning smoke on the precipitation in the clouds can be seen in the **blue color** over Sumatra and Kalimantan.

The TOMS aerosol index can be seen below:



So, does air pollution suppress or enhance overall rainfall amount from convective clouds?

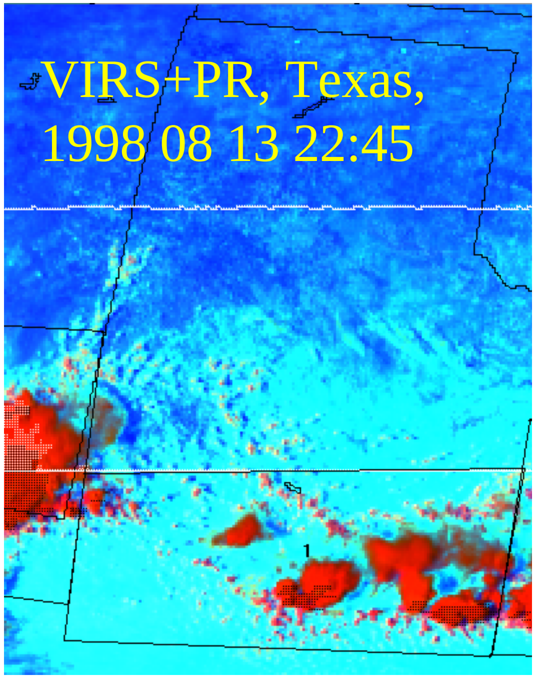
Observations and model simulations show that always clouds with more small CCN will rain less for a given maximum vertical development.

Simulations show that in warm base clouds elevating the onset of precipitation can lead to longer time of cloud growth before downdrafts take over, and hence this dynamic feedback causes greater vigor and secondary formation of clouds, leading to more overall precipitation.

Simulation of extremely continental high base (11ºC) clouds

(West Texas, August 1999)

The "polluted" Cb can have nearly adiabatic water until –38ºC
Therefore, it has very low precipitation efficiency.

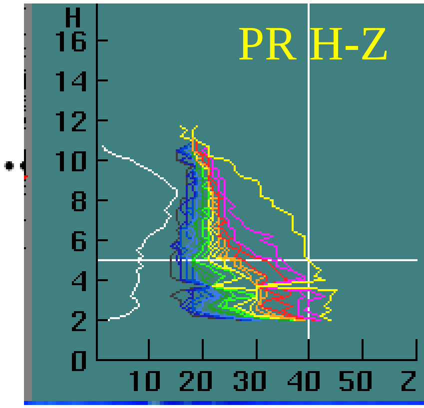


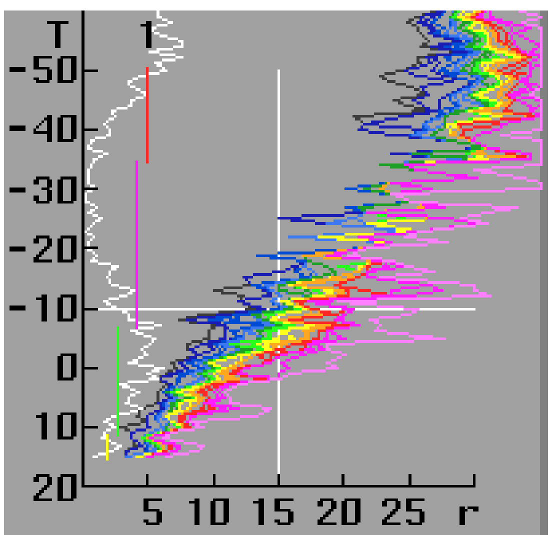
letters to nature

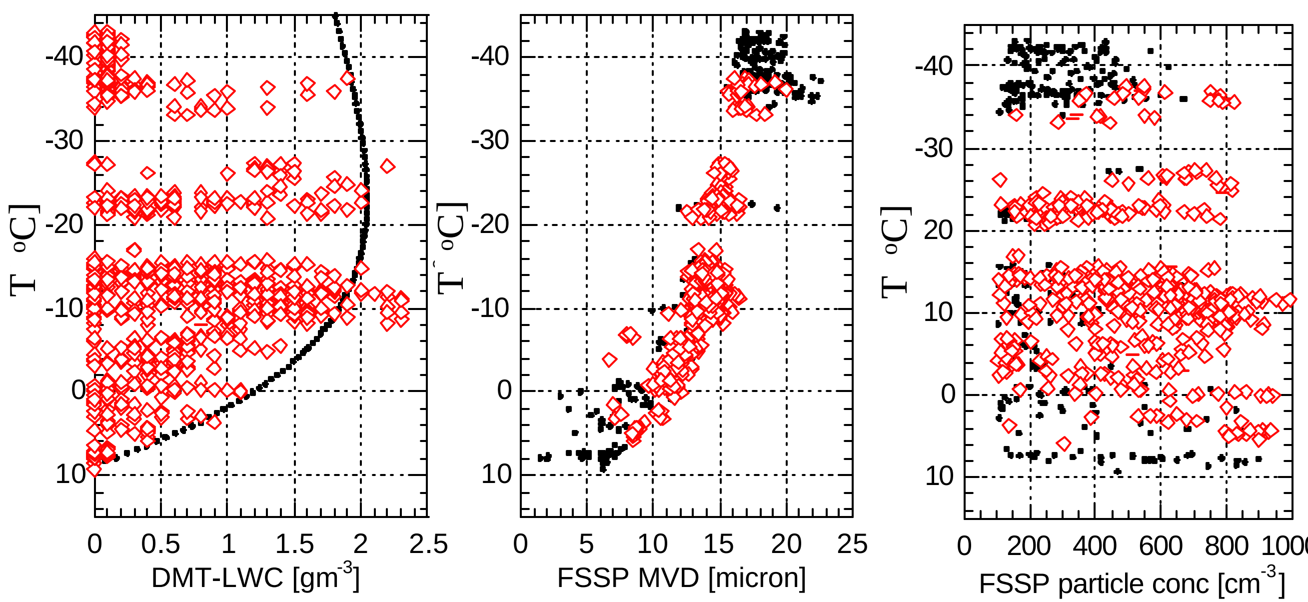
Deep convective clouds with sustained supercooled liquid water down to –37.5 °C

Daniel Rosenfeld* & William L. Woodley†

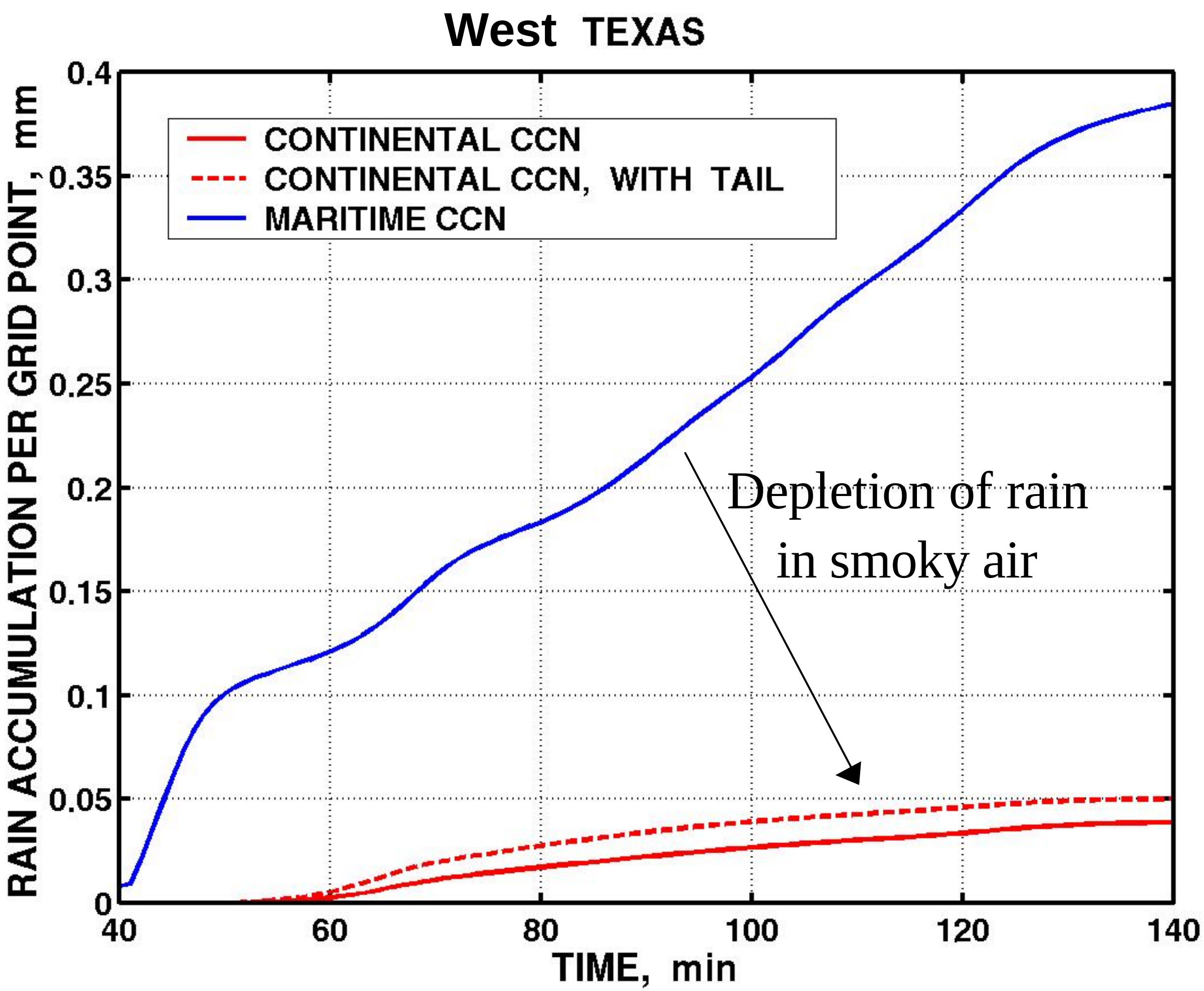
Nature, 25 May 2000, vol 405, p. 440-442.

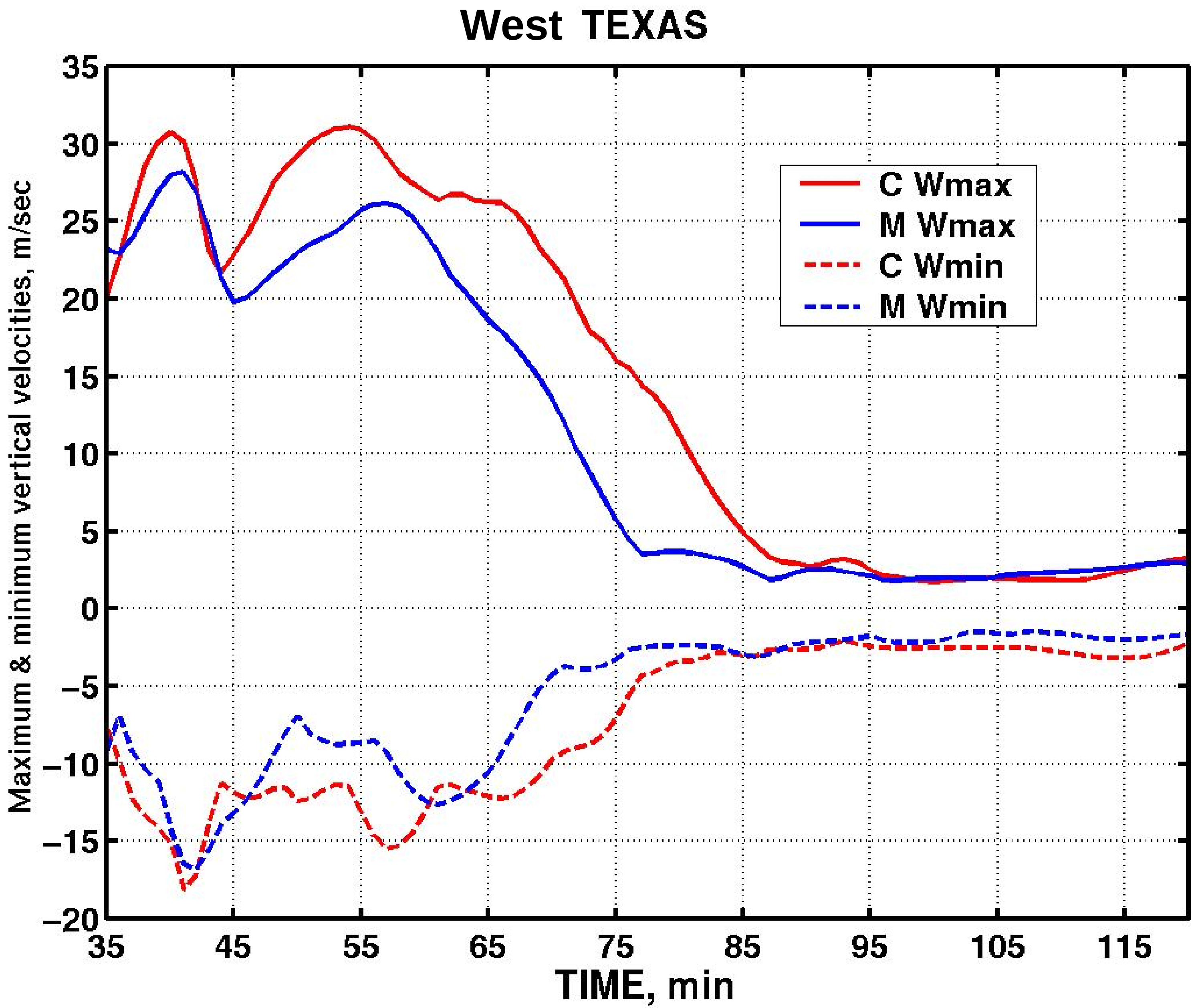






West Texas: rain accumulation

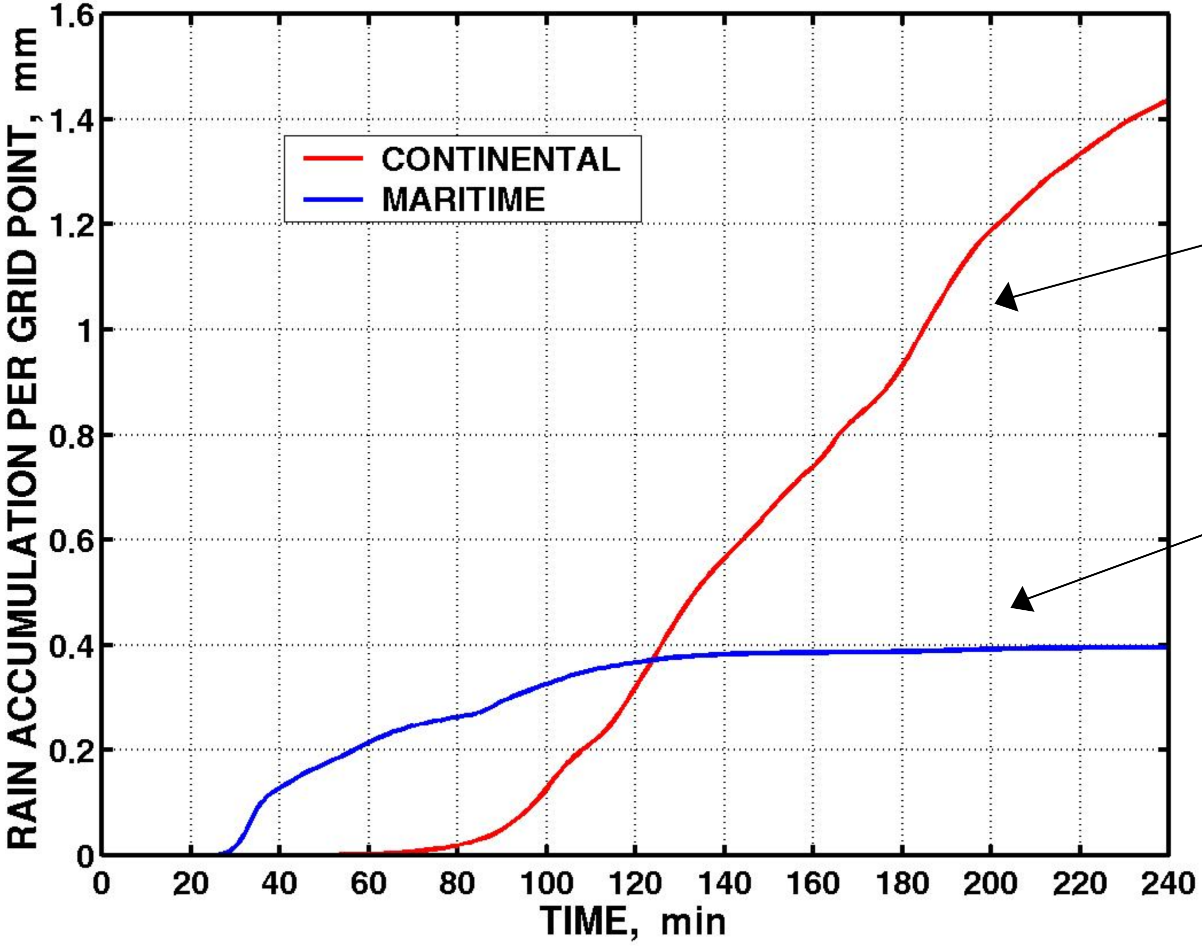



West TEXAS
C Wmax
M Wmax
C Wmin
M Wmin
Maximum & minimum vertical velocities, m/sec
TIME, min
35
30
25
20
15
10
5
0
−5
−10
−15
−20
35
45
55
65
75
85
95
105
115

Simulation of PRESTORM Alabama squall line

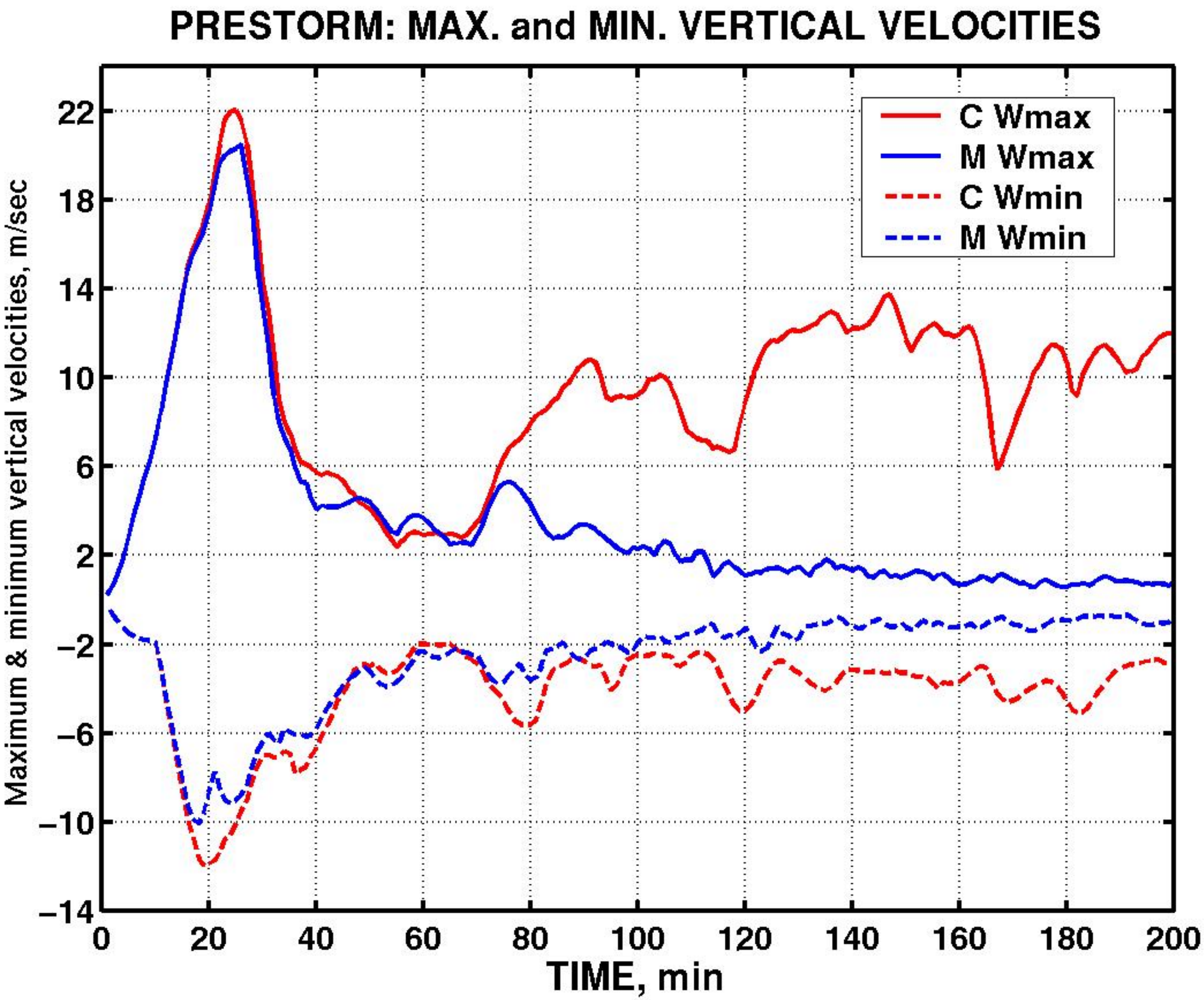
Prestorm Alabama:

Time evolution of accumulated rain

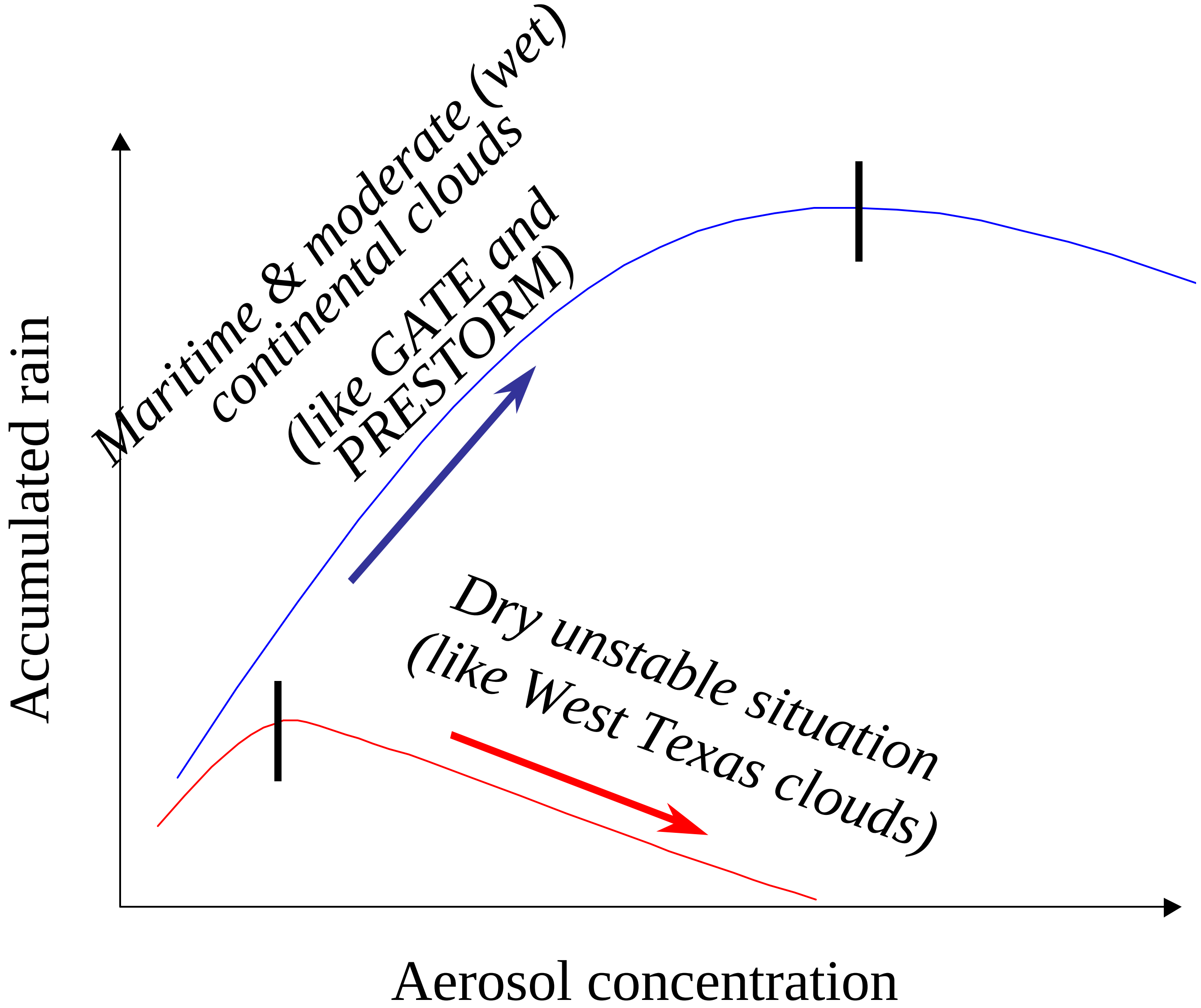


Squall line forms in smokey air !

No squall line forms in clean air !


PRESTORM: MAX. and MIN. VERTICAL VELOCITIES
C Wmax
M Wmax
C Wmin
M Wmin
Maximum & minimum vertical velocities, m/sec
TIME, min
22
18
14
10
6
2
−2
−6
−10
−14
0
20
40
60
80
100
120
140
160
180
200

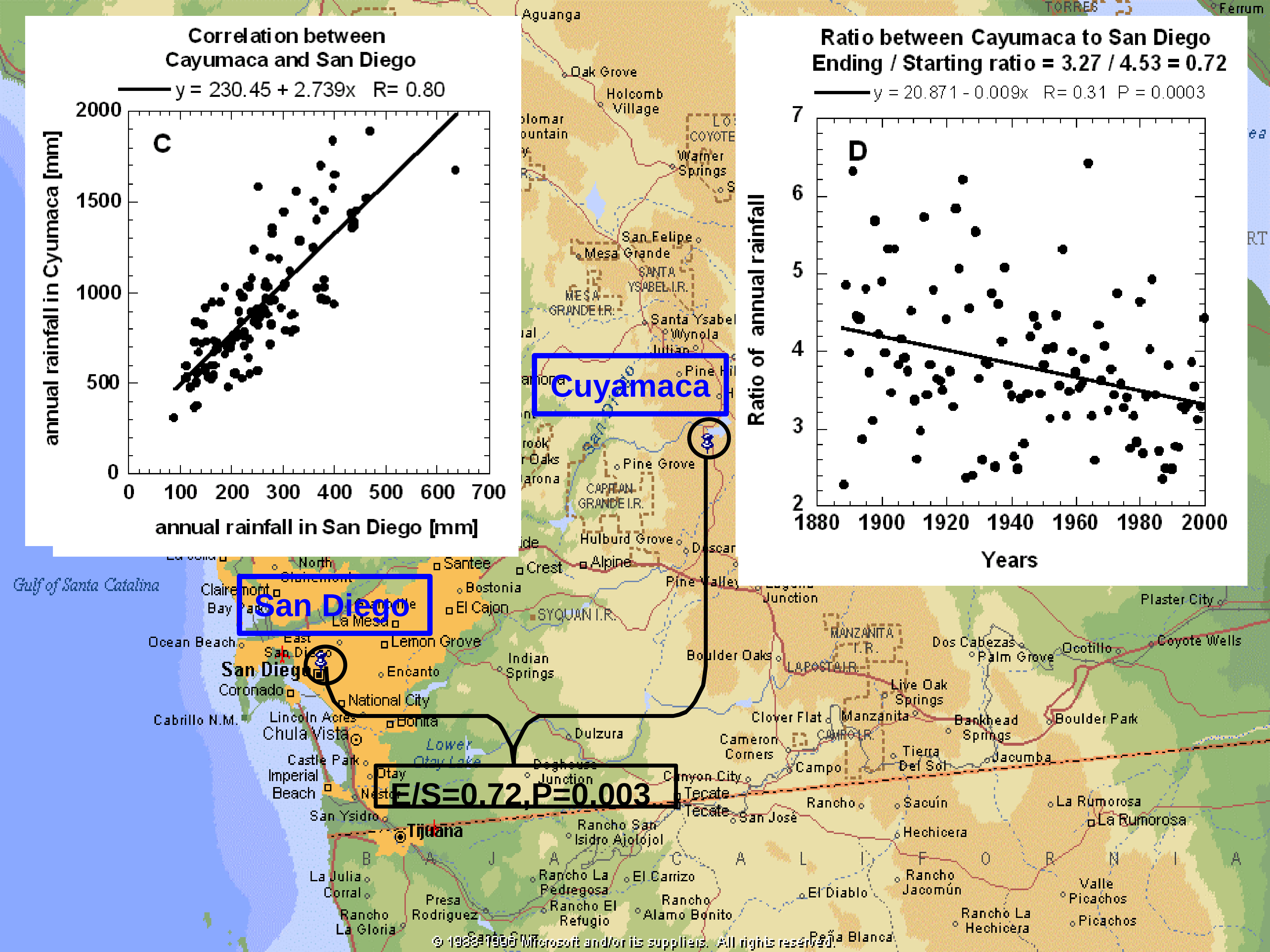
Scheme of aerosol effects on precipitation



Conclusions:

Particulate air pollution acts to delay conversion of cloud water into precipitation. This is manifested in different ways under different circumstances:

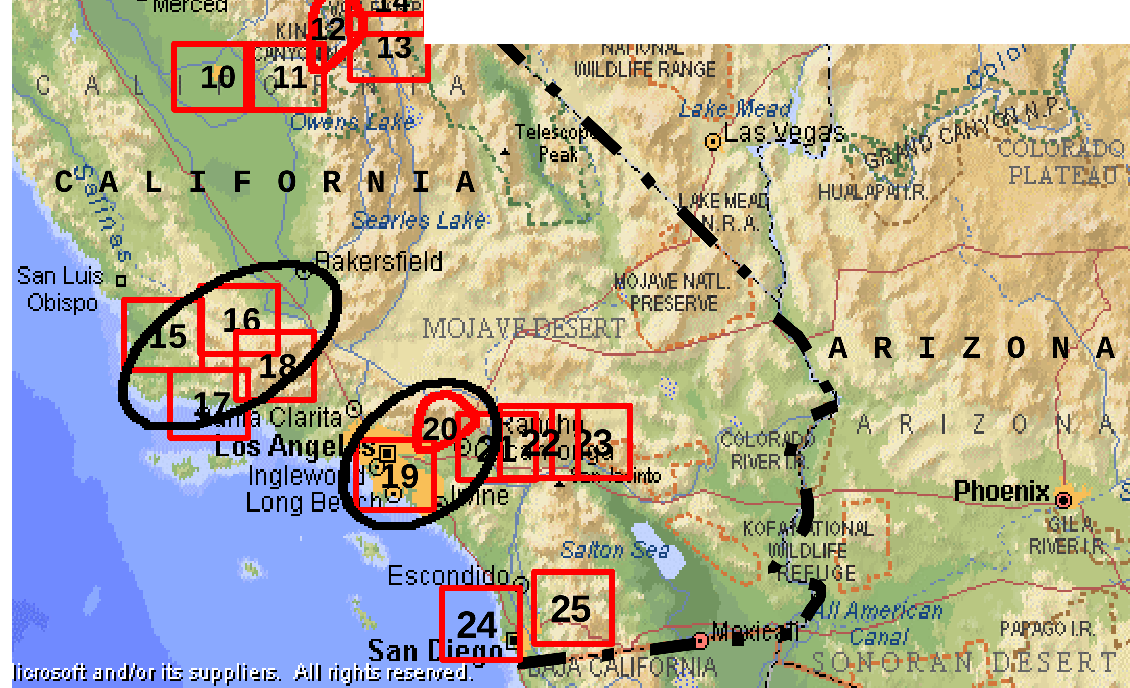
- **Orographic precipitation is suppressed, with some downwind compensation.**
- **Convective precipitation processes are delayed to greater heights in the clouds, respectively delay the downdraft and allowing the clouds to invigorate further. This causes:**
    - **In dry and unstable conditions: Reduced precipitation due to very low precipitation efficiency.**
    - **In tropical and moist subtropical conditions: Enhanced storm vigor overcompensates for the reduced precipitation efficiency.**



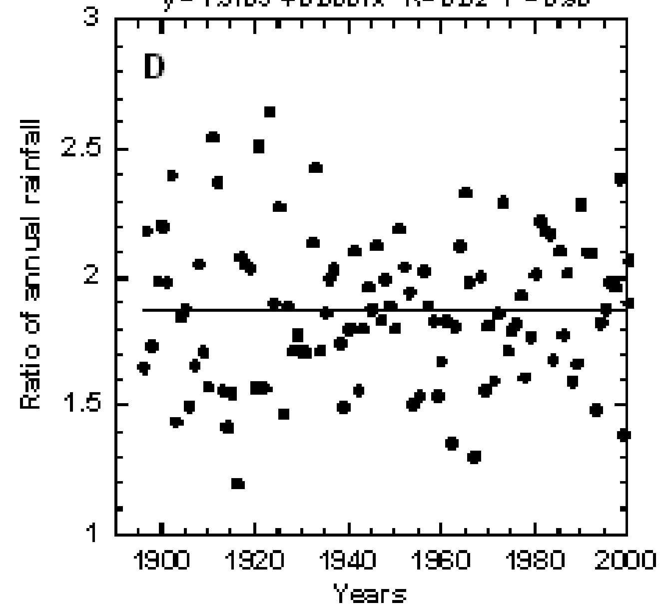
Correlation between
Cayumaca and San Diego
y = 230.45 + 2.739x R= 0.80
C
annual rainfall in Cyumaca [mm]
annual rainfall in San Diego [mm]
Ratio between Cayumaca to San Diego
Ending / Starting ratio = 3.27 / 4.53 = 0.72
y = 20.871 - 0.009x R= 0.31 P = 0.0003
D
Ratio of annual rainfall
Years
Cuyamaca
San Diego
E/S=0.72,P=0.003
© 1988-1996 Microsoft and/or its suppliers. All rights reserved.

Legend

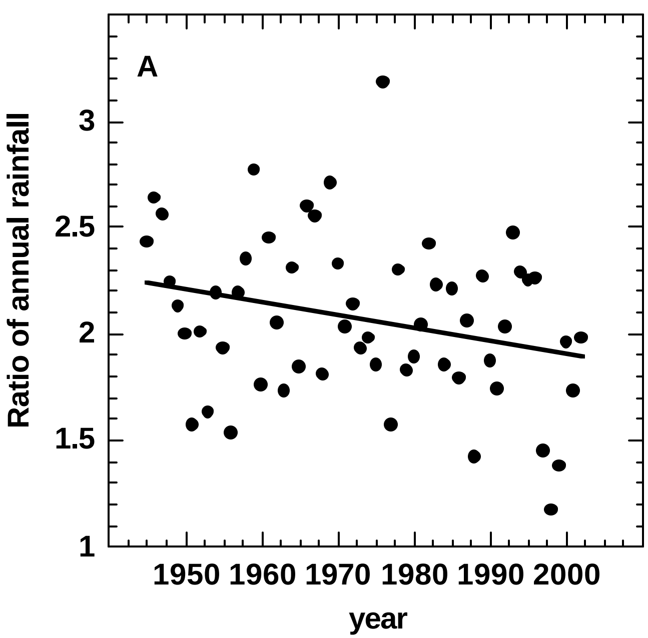
1E. Ukiah
2E. Lake Spaulding
3E. Bowman
4E. Boca
5A. San Francisco
6A. Sacramento
7A. Pacific House
8A. Cluster of snow packs in the divide line downwind to Sacramento
9A.Woodfords
10B. Fresno
11B. Grant Grove

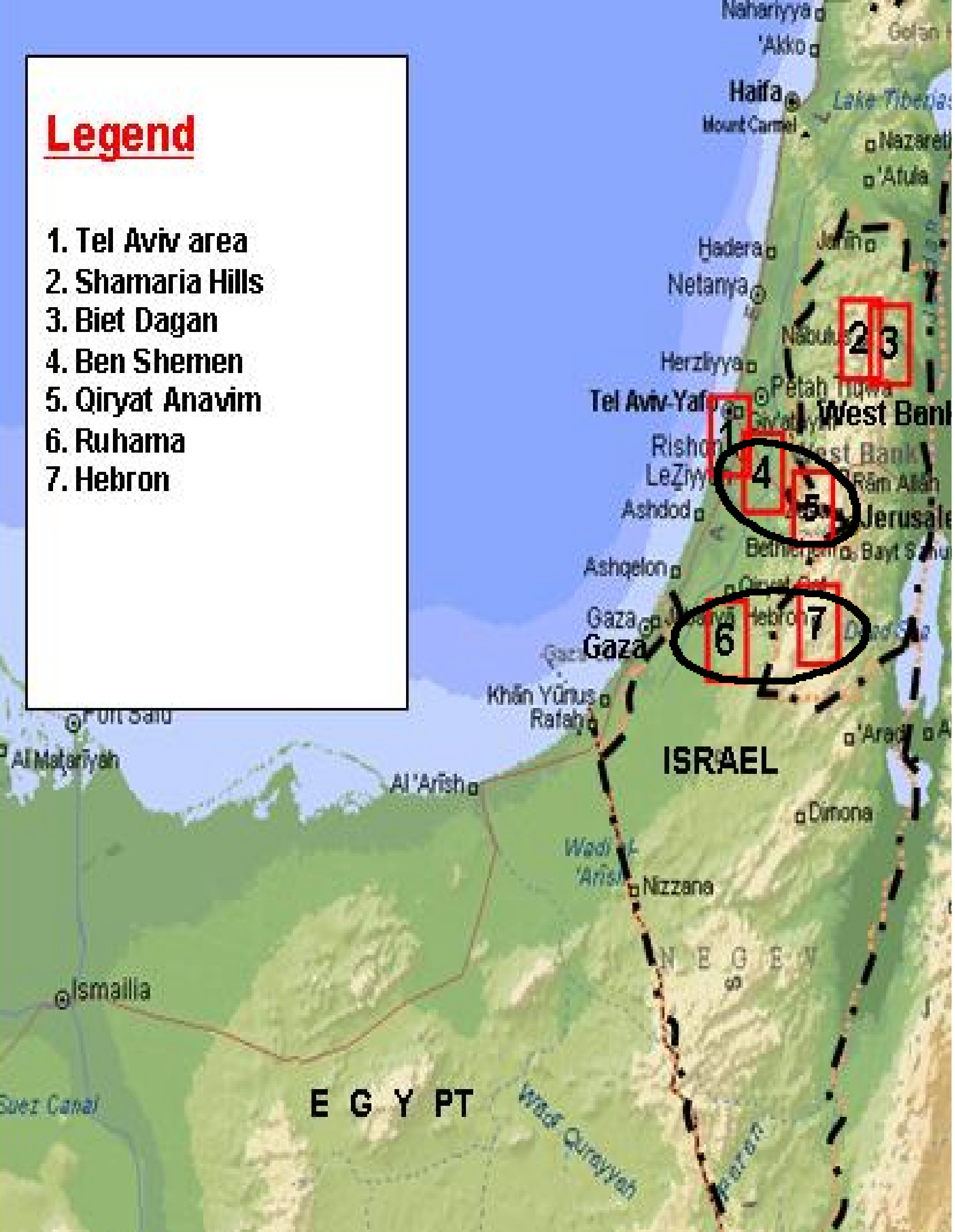


Ratio between Lake Spaulding to Ukia
Ending / Starting ratio = 1.85 / 1.85 = 1.00
y = 1.5703 + 0.0001x R= 0.02 P= 0.90

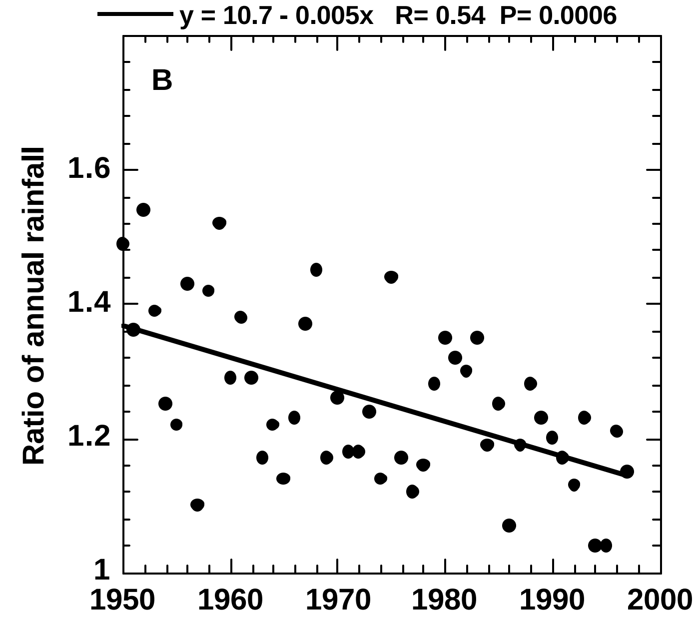


Cluster of stations: Hills downwind L.A / L.A
Ending / Starting ratio = 1.80 / 2.14 = 0.84
y = 14.25 - 0.006x R= 0.27 P= 0.03





Cluster of stations: Judean Hills / Judea plains
Ending / Starting ratio = 1.17 / 1.38 = 0.85



Startind / End ratio = 1.6/1.63 =0.98